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LUNAR SOIL MECHANICS

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Report Prepared by

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SUMMARY

This report describes a study on lunar soil mechanics conducted at the Massachusetts Institute of Technology during 1966-1967. This report has three objectives:

1. to identify those problems involved in lunar exploration that require soil mechanics for their solution
2. to identify the parameters and analytical techniques needed to solve these problems
3. to propose a lunar soil mechanics research program that will contribute to the solution of the lunar soil engineering problems.

The report concludes that research should be initiated to develop techniques for measuring soil properties both in situ and on returned samples. The ultimate goal of the proposed lunar soils research program would be to develop the ability to measure soil mechanics parameters by remote techniques, such as radar, photometric, photographic, and temperature analysis.

Another major conclusion of the report is that the research to date in lunar soil mechanics has received inadequate coordination and has lacked direction. To correct this situation, it is recommended that NASA initiate an Integrated Soils Research Program. This program should be directed by an in-house department in order to interface the research effort effectively and efficiently with other lunar programs.

As a further outgrowth of this study, the Department of Civil Engineering at M.I.T. has selected three topics from the spectrum of needed lunar soils research, and is preparing proposals to NASA. These topics are:

1) measurement of in situ strength and compressibility of lunar soils
2) measurement of in situ density of lunar soils
3) measurement of strength and compressibility of a returned lunar soil sample.

These topics seem to be important first steps in a lunar soils research program. In addition they are within the capability and interests of the Department of Civil Engineering faculty.

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CHAPTER 1

INTRODUCTION

This report describes a study on lunar soil mechanics conducted at the Massachusetts Institute of Technology during 1966-1967. The study was supported by a grant, made through the M.I.T. Center for Space Research, from the Lunar Mission Studies, Advanced Manned Missions Program of NASA Headquarters. The NASA Technical Monitor for the research was Mr. Jerald M. Goldberg and the Alternate Technical Contact was Dr. Nicholas C. Costes, Research Projects Laboratory, MSFC.

Mr. W. David Carrier, III and Mr. David J. D'Appolonia, Research Assistants in Civil Engineering, spent most of the academic year 1966-1967 reviewing relevant documents on lunar exploration, making soil engineering analyses, and reporting the results of their investigations. Dr. R. Torrence Martin, Research Associate in Civil Engineering, and Dr. Leslie G. Bromwell, Assistant Professor of Civil Engineering, participated in discussions of the work as it progressed and advised on the preparation of the report. The research was done under the supervision of Dr. T. Willam Lambe, Professor of Civil Engineering and Head of the Soil Mechanics Division.

The assistance of Mr. Goldberg and Dr. Costes in obtaining technical information was most helpful. Thanks are due Mr. Lawrence E. Beckley, Associate Director of the M.I.T. Center for Space Research, for assisting so well in the administration of the project.

The main intent of this report is to delineate the contributions that soil engineering can make in lunar exploration and to indicate the research needed to cope with lunar soil engineering problems. Consequently, the report has a threefold purpose:

1) to identify those problems that require soil mechanics for their solution

2) to identify the parameters and analytical techniques needed to solve these problems

3) to propose a lunar soil mechanics research program that will contribute to the solution of the soil engineering problems.

The diverse situations involving soil mechanics must be throughly evaluated in order to design lunar missions and hardware to meet performance requirements with minimum risk to human life and equipment. Since many of the problems that will occur in the lunar exploration program do not have a terrestrial counterpart, the development of analytical and soil testing capabilities specifically for lunar problems is imperative.

The research program proposed herein is directed toward achieving the capability for predicting site performance by remote measurements. The development of these capabilities must be coordinated with and interact with other phases of the lunar exploration program. Also, it is shown that the proposed research will require the concerted effort of many investigators over a period of several years. Therefore, it is recommended that NASA initiate an Integrated Soil Mechanics Research Program. This program should be directed by an in-house department in order to interface the research effort effectively and efficiently with other lunar programs. The envisaged NASA Soil Mechanics Department would be responsible for coordinating lunar soil mechanics research. It would award research contracts and grants and, in addition, conduct an in-house research effort.

CHAPTER 2

SOIL MECHANICS CONSIDERATIONS IN THE LUNAR EXPLORATION PROGRAM

The soil mechanics problems involved in lunar exploration fall into two general categories: stability problems and mobility problems. Stability problems include: support of structures on the lunar surface, dynamic bearing capacity for spacecraft landing, stability and settlement of lunar modules, soil and vehicle modifications, and slope stability (both natural and man-made). Mobility problems deal with the ability of a vehicle to move about on the surface of the moon. Such problems require analysis of traction and sinkage, ability to overcome obstacles, and overall vehicle surface stability. Associated with these analytical problems are the field problems of running in situ tests and obtaining samples for lab testing.

It should be emphasized that the lunar surface is not likely to be homogeneous from a soil mechanics point of view. Terrestrial experience has frequently shown a large variability in what appear to be homogeneous soil deposits. Considering the lack of detailed knowledge of the lunar surface and the hostile lunar environment, soil mechanics problems should be expected at every lunar site.

2.1 NECESSITY OF SOIL MECHANICS PREDICTIONS

The consequences of poor or overconservative soil engineering predictions can be ominous in terms of life, time, equipment, and money. Experiences of catastrophic failures on earth have indicated that careful investigations should be made even in apparently predictable situations. Moreover, even if human life and equipment are not imperiled, the savings in hardware costs that will result if good predictions of lunar soil properties are available should far exceed the research costs.

Soil mechanics problems are much less amenable to precise theoretical solutions than those of many other disciplines and therefore require a large amount of prototype testing and statistical analysis. For a number of reasons, soil engineering designs frequently rely on judgment and experience. By and large, terrestrial soil deposits are highly heterogeneous and there are no simple techniques, other than extensive sampling, for determing the extent of heterogeneity. Minor soil variations can exert a major influence on foundation behavior. Even the behavior of ideal homogeneous soil deposits is complex and not well understood. As a consequence, analytical techniques for solving soil problems usually involve gross simplifications of the actual soil behavior.

Most often, theoretical prediction techniques either depend on empirically measured parameters, or they are validated empirically before being recommended for general use. Empirical validation is accomplished only after a painstaking trial and error process which involves prediction, field measurements to check the predictions, and modification of prediction techniques to fit the field data.

Since the effect of the lunar environment on empirical terrestrial correlations cannot be assessed precisely in the absence of prototype lunar tests, terrestrial soil engineering methods cannot be applied indiscriminately. Therefore, due to unavoidable uncertainties concerning soil heterogeneity, soil behavior, and the validity of present analytical techniques, comprehensive studies of possible failure modes and soil inadequacies should be made where the consequences of failure are substantial. It should be added that lunar soil mechanics correlations will evolve, just as they have on earth; the point is that it is impossible to assume terrestrial correlations will be valid on the moon.

The degree of precision with which soil mechanics predictions are made should be consistent with hardware design limitations. That is, it is unnecessary to develop the capability of predicting settlement to the nearest inch for the first manned lunar landing if many inches of settlement can be tolerated. However, increased prediction reliability eliminates the need for overconservative designs. A simpler, more functional and possibly less expensive landing gear could be designed for the Early Apollo flights if it were possible to predict with, for example, 99.9% certainty that the sinkage of the LM will be less than 10 inches. Of course, the cost of acquiring sufficient information to make such a prediction may be many times greater than the savings realized in landing gear design. Thus, to obtain the most efficient use of soil mechanics, the level of knowledge required for accurate prediction capabilities must be optimized with respect to mission requirements and other design limitations. However, a basic understanding of the behavior of lunar soils is necessary before design trade-offs can be made.

2.2 SOIL MECHANICS PROBLEMS

2.2.1 Foundations

During the entire duration of the lunar exploration program, foundation problems will be encountered each time that a Lunar Module lands on the moon. The soil engineering objective with regard to foundations is to predict the amount of movement that foundations will experience under given loading conditions. Once this is accomplished, foundations can be designed to prevent tilting or sinkage sufficient to impair the performance of the structure. The accuracy required for predicting movements is necessarily a function of the design constraints of the landed module.

As an example, if we consider the lunar soil to be elastic, the settlement of one LM footpad equals $0.0117 \times P/E$, where P = load in pounds on one leg and E = modulus of elasticity of soil in pounds per square inch. If the settlement must be less than 10 inches, then E must be greater than or equal to 1.2×10^{-3} P; if less than one inch, then E greater than or equal to 1.2×10^{-2} P. Thus, the required accuracy of E depends on both the allowable settlement and the applied loads; i.e., the accuracy is a function of the design constraints.

Large allowances for sinking and tilting of the LM on the initial lunar missions are a result of major uncertainties concerning the physical properties and behavior of the landing sites. With a better understanding of the engineering properties of the lunar surface and an increased capability for predicting the properties of a specific landing site, the number of foundation design variables can be reduced or more precisely specified. Having a more accurate estimate of the factor of safety will permit operations at sites that would be rejected without this knowledge, or conversely, such information may eliminate certain sites. Furthermore, future facilities will benefit from the more accurate designs that will be possible.

The foundation requirements imposed on lunar missions will be diverse. For the initial manned landing the tolerances of seven degrees maximum tilting from the local vertical and 44 inches of total sinkage have been established for the LM. Such requirements will undoubtedly become more stringent for LM shelters, laboratories, and observatories. Although time-dependent movements are of secondary importance to the first manned landings, they will be particularly undesirable for lunar observatories and laboratories where complex equipment must remain in a fixed position for long periods of time.

All vehicles currently under development will land on the moon using essentially the same procedure. In order to properly design the LM suspension system, landing gear and footpads, it is essential to predict the lunar soil response to dynamic loading. Thus, landing dynamics analysis requires the prediction of soil-LM interaction during touchdown, as well as dynamic bearing capacity, settlement, and potential rocket exhaust erosion problems.

The static bearing capacity of the lunar surface is the maximum bearing stress that can be applied without causing a shear failure of the supporting soil, which would result in gross movements of the LM. Bearing capacity is not an intrinsic soil property; it is a function of loading geometry as well as soil strength. In terrestrial experiments on sands, the static and dynamic bearing capacity have been found to be essentially equal until the failing mass is accelerated to about 10 g or more

($g=980$ cm/sec^2). The greater the acceleration, the greater the dynamic bearing capacity. In addition, the static soil strength may decrease due to disturbance during landing and/or contamination by rocket exhaust. The bearing capacity on a sloping surface will also be less than the bearing capacity on a horizontal surface, assuming all other factors are equal.

Initial settlement will occur even if a bearing capacity failure does not occur. Soil disturbance and contamination may also result in increased deformations of lunar soil during and after landing, which together with soil consolidation may cause significant time-dependent total settlements and differential settlements. (Settlement is divided into three components: initial settlement, primary consolidation, and secondary consolidation).

Since it will not be possible to land a module precisely on a predetermined position, it may be necessary or desirable to stabilize the foundation soil or modify the LM facitity after landing to prevent loss of the vehicle or detrimental movements.

At this time, there is no way of quantitatively evaluating an Apollo site prior to landing unless a Surveyor probe is sent ahead. Even then there are problems, since the Surveyor may land some distance away from the Apollo site. It is thus economically justifiable to be over-conservative on the early missions. On the other hand, we have no way of determining how over-conservative a design really is; even after successful landing, time-dependent phenomena may cause a catastrophe, such as gross failure or excessive differential settlement.

Thus, a thorough site evaluation should be conducted after landing to insure against unexpected developments. This evaluation might consist of placement of surface instruments to warn of movements of surrounding soil, as well as instruments on the vehicle to warn of excessive settlement or impending instability. If the site evaluation indicates that it is necessary, site improvement may be carried out by modifying the facility and/or the soil. Facility modifications might be accomplished by establishing anchor lines; soil improvements by the injection of a solidifying gel. This type of site evaluation is actually a crude in situ test and thus will aid in designing future missions .

Seismic activity on the moon, if it exists, will also affect foundation design. It is not clear yet whether Moonquakes are occuring, but the Orbiter photographs indicate that definite downslope movements of the surface material have occurred. Whether from internal or external sources, the effect of seismic vibrations on the strength and deformability of the bearing soil must be considered in foundation design.

2.2.2 Mobility

Vehicle mobility is more difficult to predict accurately than foundation stability, because the theoretical parameters of the mobility equation are not well defined and rely to a large extent on empirical correlations. Moreover, lunar soil properties and behavior must be evaluated over the entire traverse route for mobility problems rather than only at specific sites as with foundation problems. Analysis of long-range vehicles (such as MOBEX) must be more comprehensive than that of LSSM-type vehicles, not only because the LSSM operators will have walkback capabilities, but also because the long-range vehicles will encounter far greater variations in terrain.

As with foundations, mobility problems involve an analysis of the shear strength and compressibility of the lunar surface. Mobility problems differ from foundation problems in that the load applied by the vehicle is transient. Thus, vehicle mobility is dependent on the complex interaction among frictional, cohesive, and inertial forces in the soil beneath the wheels; and the mass, inertia, and geometry of the vehicle.

The net traction of the vehicle is a function of the force required to shear the soil under the vehicle footprint and the rolling resistance due to soil sinkage. Quantization of these variables for terrestrial mobility problems is empirical and often unsatisfactory. The influence of the extreme lunar environment on the semiempirical formulation of the wheel traction equation is not known precisely, but as pointed out in Appendix B, it is an over-simplification to assume that these semi-empirical relations will hold for the lunar surface.

Another consideration in the design of lunar roving vehicles is the ability of the vehicle to negotiate small obstacles not requiring circumnavigation. An analysis of this ability is important for assessing the power requirements of the vehicle in addition to specifying mobility constraints on unnavigable terrains. For this purpose, analyses must also be performed to determine the overall stability of the roving vehicle on slopes.

2.2.3 Slope Stability

Slope stability problems involve both natural slopes and man-made slopes. Natural slopes will be of greater concern in the early phases of lunar exploration. Among the situations that must be analyzed are stability during spacecraft landing and launch, and stability during astronaut and/or vehicle traverses. As was mentioned in Section 2.1, slope stability problems are among the most difficult problems in soil engineering. This is a case where large factors of safety will be necessary until more information regarding the actual soil conditions is available.

Problems with man-made slopes occur during excavations, embankment construction, instrument emplacement, etc. In later stages of the lunar exploration program, cut and fill operations may be very important for underground construction, using the lunar soil as a shield against radiation and meteorites.

2.3 SOIL MECHANICS PREDICTION TECHNIQUES

Natural earth soils are non-homogeneous, anisotropic, highly non-linear, inelastic, and time-dependent. Moduli and strength parameters are dependent upon stress system as well as stress level and can be established only for particular loading conditions. For these reasons, no generalized stress-strain law has been developed for terrestrial soils and, therefore, an integrated, straightforward, theoretical solution to soil mechanics problems does not exist.

Essential steps in the solution of soil engineering problems include: 1) predicting soil stresses prior to and after loading; 2) securing representative, undisturbed soil samples; and 3) measuring the soil's response when the predicted stresses are applied. When possible, in situ tests are conducted as a supplement to, or in place of, laboratory tests.

Two limiting types of analysis are used to study terrestrial soil deformation and stability. If the applied stresses are significantly less than the soil strength, elastic theory is used to predict stresses. Laboratory soil specimens are subjected to the computed stresses and the resulting strains are measured. The measured strains are assigned to corresponding soil elements in the ground and integrated to obtain the total deformation. When the applied stresses approach the soil strength, limiting equilibrium analysis is employed. This analysis assumes that plastic zones in the soil are continuous and constitute a failure surface. A free body is considered to be bounded by the failure surface and the ground surface; sufficient assumptions are made to render the stresses acting on the free body statically determinate and the shear stresses acting on the failure surface are computed. The shear strength of the soil is determined experimentally. A factor of safety is computed as the ratio of the average shear strength of the soil to the average shear stress mobilized on the failure surface.

In general, reasonably accurate predictions can be made of load and deformation for low applied stress levels and for predictions of the ultimate load. Recently, improved techniques for predicting the load-deformation relationship between these two extremes have been developed using finite-element, elastic-plastic models.

Analysis of soil dynamics problems follow similar procedures: 1) predict dynamic stresses and accelerations using elastic theory or limiting equilibrium, 2) subject laboratory samples to the computed stresses and accelerations and measure the response of the soil.

Examples of solutions for bearing capacity and settlement problems are presented in Appendix C.

Mobility problems also directly involve the strength and deformability of the surface material. However, because of the substantial difficulties involved in predicting the complicated stress conditions under vehicle wheels, the problem has been approached using semi-empirical techniques. These techniques do not use fundamental soil properties; they are based on parameters established by correlations between an empirical soil test and trafficability.

CHAPTER 3

LUNAR SOIL MECHANICS RESEARCH

The previous chapter outlined the basic soil engineering problems in lunar exploration; this section recommends a research program for investigating these problems. The objective of the research program is the remote prediction of site performance for both foundation and mobility problems prior to astronaut landing. The proposed research is evolutionary in that, concurrent with the development of the capability to solve problems pertinent to the current phase of lunar exploration, the over-all research program systematically progresses toward the achievement of the long-range goal.

The program is directed towards developing the best possible prediction capabilities for the currently highest priority soil engineering problems for a given amount of research effort. Determination of the priority for each soil situation is an iterative process which must be carried out by NASA. As an example, consider the mobility problem: first, very conservative conditions are assumed for the lunar surface--say a lightly cohesive ($c = 0.1$ psi), highly porous soil ($\phi = 10°$); then an estimate is made of how much it would cost to build a vehicle to perform the required task. More than likely, the price tag is much too high. By assuming more favorable soil parameters, a new vehicle estimate is obtained that is much lower--but now an estimate must be made of the research cost required to be sure the parameters are at least as good as have been assumed. Hopefully, the sum of the two components is less than the cost for the most conservative design.

The iterative process is repeated until a minimum total cost is reached; beyond this point, the cost of the required data begins to increase faster than the cost of the vehicle decreases. The optimum point is not necessarily the minimum total cost, however, since the conditions may not actually be as good as have been assumed for the design involving the minimum cost. In addition, the cost estimates for the vehicle and the soil must consider such factors as: astronaut safety, time-delay between return of data and completion of vehicle, and savings that will accrue to other activities as a result of better soil data.

Once the optimum solution is obtained for each activity, the activities can be considered as a whole and an optimum soils research program can be developed to solve a given set of problems at a nearly minimum cost. As the program evolves, and more information becomes available, earlier cost estimates will, of course, have to be modified.

The recommended research program has been divided into two categories: 1) development of capabilities for remote prediction of soil properties and behavior of specific sites; and 2) development of analytical techniques for solving engineering problems. Although knowledge in both categories is essential for predicting site performance, the need to obtain a good understanding of the mechanical properties of the lunar surface far exceeds the need for new theoretical research at the present time. Thus, research directed towards determining lunar surface properties and behavior has the higher priority.

3.1 LUNAR SOIL PROPERTIES AND BEHAVIOR

Research in three major areas is required to achieve the objective of being able to predict soil properties and behavior at various sites using remote measurements:

1. Specific site studies - comprehensive lunar and earth testing program to determine the properties and behavior of the lunar surface material;
2. Classification parameters - establish measurable parameters for comparing the soil at one lunar site with that at another site;
3. Correlation techniques - develop techniques whereby classification parameters can be measured by remote methods.

The first two areas are interrelated; by making detailed measurements at specific sites the basic material properties that distinguish soil behavior at one site from the behavior at another site can be isolated and expressed numerically. Tactile measurements made during the Apollo program could be used to establish correlations between classification parameters and engineering behavior. Remote sensors could then be used to measure the classification parameters rather than the engineering properties. This approach is considered realistic, since remote techniques, such as radar, are related to parameters such as material type, grain size distribution, and porosity rather than engineering properties, e.g., strength and deformability.

The accuracy with which indirect measurements can be used to predict engineering behavior cannot be estimated prior to the initiation of the research program. Therefore, the number of indirect predictions that must be validated by on-site observations is not known. If predictions by remote measuring techniques are not sufficiently accurate for all engineering situations, direct measurements of material properties and/or engineering behavior must be made. The suggested research program is developed in such a way that if predictions by remote measurements prove to be of limited use, the capability of making direct measurements will also have been developed. However, the overall program in its most general form must be initiated before sufficient information is available to establish trade-offs among 1) development of remote prediction capabilities, 2) tactile surface measurements, and 3) increased conservatism in hardware design.

3.1.1 Specific Site Studies

Specific site studies are required to obtain detailed information on soil behavior, which has direct engineering applications; and on soil technology, which has scientific applications as well as being useful in interpreting engineering behavior. With regard to soil behavior, two general types of information are required: 1) in order to determine the engineering properties of lunar soil, it is necessary to conduct many strength and deformability tests on both reconstructed lunar samples that are returned to earth and on simulated lunar soils; 2) sufficient data concerning the in situ state of the lunar surface material must be obtained; to determine both strength and deformability of the lunar surface material directly, in situ tests on the moon are needed. The in situ lunar tests can also be used to check the validity of predictions based on earth testing and eventually to check remote sensing data.

Soil technology, the study of the physico-chemical properties of soils, in addition to providing an understanding of the mechanisms controlling the strength of soils, is important in establishing the classification parameters influencing soil behavior.

Required Soils Data. The solution of deformation and stability problems involving soil requires a knowledge of the strength and stress-strain behavior of the soil. The numerical values of the parameters that are used in a specific analysis depend on a large number of factors. It is usually impossible to take the results of a test designed to approximate one set of conditions and apply them to other different situations directly. That is, to give precise values, laboratory and field tests must be designed to approximate the specific conditions applicable to the particular engineering problem at hand.

However, it will be possible to obtain rough estimates of soil parameters by conducting very simple tests on the moon (Surveyor and LM footpad identation, trenching, observation of astronaut footprints, simple penetration tests, etc.). The computed soil parameters can then be used for approximate analyses of bearing capacity, traction, settlement, and slope stability. Some of these simple tests have already been run, with varying degrees of success. The Surveyors, for instances, have yielded values for bearing capacity (see Appendix A). Unfortunately, the three parameters involved in the bearing capacity; namely, ϕ (friction angle), c (cohesion), and γ (unit weight) could not be separated from each other. Thus, to evaluate one parameter, it is necessary to assume values for the other two. The results did give a range of possible values, however. Similarly, the trenching experiment on Surveyor III provided some information on slope stability. But again, the three parameters ϕ, c, and γ could not be separated from each other.

However, even if the parameters could have been determined separately, they could not be used indiscriminately. For instance, soil engineers do not run plate bearing tests (e.g., Surveyor footpad sinkage) for a mobility analysis; correlations do not exist for transforming ϕ and c measured by the former to the parameters used in the latter. That is not to say that such correlations cannot be developed; but the cost is likely to be high. When estimating the cost of a probe, it is necessary to consider the cost of evaluating the data for situations other than that for which the probe was specifically designed. Also, depending on the accuracy required it may be necessary to establish these correlations on the lunar surface rather than depending on terrestrial simulation alone.

A thorough research program must determine the effects of the following factors on the strength parameters (friction and cohesion) and the deformation parameters (Young's modulus and Poisson's ratio and/or Compression Index):

A. Environmental Factors

1. Temperature
2. Radiation

3. Atmosphere (including contamination)
4. Time
5. Electrical charges

B. Material Factors

1. Mineralogy
2. Particle size, shape and distribution
3. Density
4. Structure

C. Loading Factors

1. Stress Level
2. Amount of strain
3. Previous stress history
4. Rate of loading
5. Orientation of stresses
6. Repeated loading
7. Vibrations
8. Impact loading

Once this type of data has been obtained it will be possible to evaluate nearly all foundation and mobility problems involving soil mechanics. Eventually, once enough data is accumulated, it may be possible to make geologic inferences from stress-strain characteristics, such as maximum past overburden stress.

Soil technology helps to explain soil behavior in fundamental terms and therefore is a valuable aid to the soils engineer. Because soil technology is scientific in nature, many of the experiments mentioned here are planned by other groups, and thus a great deal of cooperation is possible. The following types of tests have been suggested by approved experimenters for the first samples:

1. Elemental and mineral composition (optical, X-ray, electron microscope, etc.)
2. Radioactivity
3. Textural analysis
4. Density of individual phases
5. Impedance and dielectric properties
6. Reflectivity
7. Porosity
8. Thermal behavior

In addition, such factors as gravity, meteorite impact, and shock metamorphism must be explored to determine their effect on the depositional or soil-forming process. These factors affect particle size, packing geometry, and particle to particle contact forces. Thus, they also influence the engineering properties. Soil Technology, when applied to terrestrial situations, is able to identify the environment in which certain soil deposits were formed. Soil Technology may be able to accomplish the same thing when applied to lunar soils, and thus provide clues to the origin and history of the moon.

Acquisition of Material Properties. There are three regimes of testing to obtain the required data for use in the specific site study analyses: in situ tests; earth based laboratory tests; and lunar based laboratory tests. In all three areas, astronaut training in the use of equipment and selection of samples will play an important function. Astronaut training should consist of an integrated program of classroom, laboratory, and field work.

In Situ Lunar Tests. There are a wide variety of in situ tests that can be performed on the moon. These include tests to measure surface properties and behavior directly, and prototype and model tests to verify engineering predictions and to establish correlations between the performance of structures and vehicles on the moon and lunar soils properties. The types of in situ tests that should be conducted include the following:

1. Instrumented package landed on the surface
2. Penetration probes
3. Plate bearing and shear tests
4. Density and structure tests
5. Geophysical measurements
6. Instrumentation of vehicles and of LM landing assembly.

The purpose of conducting in situ tests to determine strength and deformability is twofold: by performing a number and variety of in situ tests, the homogeneity of the surface material, both laterally and with depth, can be determined; and since earth-based tests will necessarily be performed on reconstructed samples, in situ measurements provide the only means for determining the validity of the earth-based tests. In order to reconstruct disturbed lunar samples on earth that have the same structure and density as the in situ material, it is necessary either to develop practical methods for measuring structure and density in situ, or to develop an undisturbed sampling device, or both.

It is essential to monitor and to evaluate the performance of all spacecraft landed on the moon, of all vehicles used on the moon, and of all structures built on the moon, in order to determine the reliability of engineering predictions and to assess the current design procedures. A program for measuring actual loads and movements should always be made a part of the design.

Many experiments can be performed in conjunction with previously planned operations. In general, these experiments would consume minimal amounts of the astronaut's time. For example, the astronaut's walking staff could be modified to serve as a simple penetrometer. Photographs of astronaut footprints could be used to study the lateral homogeneity of the lunar surface; they also could be used with other data to estimate bearing capacity and settlement factors. (For example, a returned sample could be reconstituted to the density that yielded the same sinkage under a load corresponding to an astronaut's foot. The sample could then be tested to determine strength and deformability). Records of power input and rate of penetration of the lunar drill will provide indications of rigidity, strength and density as a function of depth. Photographs of the LM footpads at several time intervals after touchdown can be used to establish the amount of settlement and the existence of time-dependent settlements. Many simple experiments could also be performed automatically during vehicle traverses. During individual excursions the astronauts may either run a test on an undisturbed sample during their stay on the surface (such as direct shear) or set up a test which will be run by remote control after the astronaut has departed.

For example, the astronauts might load an apparatus with ten carefully selected undisturbed samples. Then automatically or by remote control, the device could run a series of tests involving shear and compression.

Any test that is considered on the moon must be automated and as simple to operate as possible; astronaut time would be far too costly otherwise. Much of the technology required for automating in situ terrestrial soil tests already exists and probably could be adapted and developed for lunar use.

The entire area of in situ lunar testing deserves careful and considered attention. Soil mechanics predictions cannot be considered reliable until they are verified by in situ performance. A major effort should be devoted to determining the type of tests that can be performed economically on the moon and that also provide the largest return of pertinent information.

Earth Based Laboratory Tests. During early Apollo the bulk of the soils data will be obtained from tests on returned samples. Most of these data will be of limited engineering value for two reasons: 1) the samples will be representative of only the surface layer; and 2) the samples will probably be badly disturbed; due not only to sampling, but to re-entry and landing forces. The problem of sample representativeness and sample disturbance cannot be avoided during the first missions. However, at the outset, engineering data must be obtained in order to make meaningful engineering decisions later in the lunar exploration program. In addition, data from returned samples will provide the only means of correlating other data, including qualitative observations.

The initial problem in conducting earth based tests on returned or simulated lunar samples is to reconstruct samples having the same material properties, the same fabric and porosity, and the same environment as the in situ lunar soil. It is likely that the engineering properties are influenced by reversible environmental factors (such as atmosphere and electrical charge). Thus, if the environment can be duplicated on earth and if the sample is reconstituted to its in situ density, reasonable agreement with in situ mechanical properties is likely. An experiment to measure the in situ density is essential to earth-based testing. Not only is this parameter important for running engineering tests, but its value is also needed to interprete measurements of thermal inertia constant: radar reflections: and geophysical tests (part of ALSEP package). There is no question that the density of the lunar soil must be measured as early as possible, preferably on the first or second mission. In addition, the technology required to perform appropriate compression and shear tests under high vacuum conditions and on small samples must be developed. Research and development in many of these and other areas can be initiated prior to the first lunar landings.

Once lunar samples become available a program of research and testing should be initiated to determine the effects of the various factors enumerated in Section 3.1.1 on strength and deformability. This program should include:

1. Shear Tests
2. Compression tests
3. Bearing capacity tests
4. Trafficability tests
5. Friction tests
6. Dynamic tests.

By using the results of research conducted on soil behavior and soil technology, it will be possible to synthesize the lunar soil on earth; that is, model the lunar soil with terrestrial material that has similar strength and deformability characteristics. These models can then be used for mobility and foundations studies. Of course, the lunar soil is likely to be quite heterogeneous; thus, the degree to which the lunar soil is duplicated on earth will depend on the accuracy required in the solution. The degree of duplication also depends on its intended use. If mobility were the only concern, then only a relatively shallow layer of soil would have to be manufactured; however, if bearing capacity were being modeled, then the subsurface soil would also have to be duplicated. Establishing criteria for obtaining the degree of similitude required for various problems is an important research area.

Obviously it will not be feasible to simulate all conditions inherent to the lunar surface and the lunar environment. The effects of neglecting certain factors in model testing must be evaluated, and compensated for if possible. Traditionally, in terrestrial soil mechanics, soil engineers have not had to perform extensive model tests and as a result this technology is not well developed. Therefore, research must be undertaken to develop similitude criteria for soils if full utilization of the potential value of modeling techniques is to be achieved.

In regard to the use of the models, it is interesting to compare the field of hydraulics with that of soil mechanics. The former has a long history of dimensionless parameters, such as the Reynolds, Froude, Weber, and Mach numbers. Hydraulics is also known for its large-scale models, such as the Corps of Engineers model of the entire Mississippi River Basin. Until recently, none of this was found in soil mechanics. Simlitude is beginning to play a large role in the solution of mobility problems; it is certain that other soils problems will also be studied by this approach in the future.

One of the simulations that could be conducted on synthesized lunar soil deserves special mention: soil improvement. Soil improvement could play an important role on the moon, just as it does on earth. As the environment of the moon and the operational constraints present major difficulties that are not encountered on earth, the techniques of application will probably be a most difficult problem. Soil improvement could be used primarily for the stabilization of LM sites before or after landing. Stabilization might consist of: increasing bearing capacity, decreasing settlement, or eliminating the problem of rocket exhaust erosion. Stabilization techniques such as the injection of a hardening gel should be studied. During later phases of exploration soil improvement offers the exciting possibility of using the soil as a construction material for roads and buildings or for stabilization of excavations and tunnels. If this becomes a reality, it will mean a substantial savings in materials that would otherwise have to be ferried to the moon.

Lunar Based Tests. Due to restrictions on astronaut time and operational limitations during the early missions, earth based testing must be the major source of soil mechanics information. As soon as it is practicable lunar-based testing should assume part of this role, as in the long run in situ tests will be far more economical than earth-based tests. The Surveyor photographs indicate that at least some of the lunar soilis a weakly cohesive,loose material. It is doubtful that undisturbed samples of such soil could be returned to earth; it is difficult to obtain good terrestrial soil samples, without the disturbing effects of launch, re-entry, and landing. For engineering purposes and for certain scientific tests it is absolutely necessary to have undisturbed samples: measurements of strength and deformability of remolded samples are of limited value; likewise fabric, porosity, thermal behavior, reflectivity, and electrical properties. Tests on the moon would also involve minimum contamination of particle surfaces, since lunar tests can be run without leaving the natural enviroment of the lunar surface.

As soon as it is operationally feasible a soils laboratory should be established on the moon. It is recognized that such a laboratory may not be feasible during the early stages of lunar exploration. On any of the individual excursions the scope and sophistication of the tests will always be severely limited by operational problems. For this reason, a soil mechanics laboratory to complement the field testing is necessary. Such a laboratory could essentially do all the testing formerly done on earth and could also include any new tests that have been developed especially for lunar soils. Automation of the equipment would be emphasized, but specially-trained astronauts will be required to operate the equipment.

A lunar soils laboratory, of course, assumes a long-range commitment to exploration of the moon.

3.1.2 Classification Parameters

Required Data. There are two types of information that are required to classify a given site. First, the relationships between stress-strain-strength characteristics and the soil type, porosity, fabric, and other identifying factors must be known. Second, the homogeneity or variability of the soil vertically and horizontally must be characterized. If this information can be obtained by remote techniques at sites for which we already have tactile data (gathered during Specific Site Studies, as described in Section 3.1.1), it will be possible to use remote techniques at untested sites and make a probabilistic prediction of strength and deformability.

Methods for Obtaining Data. The first step is to develop a capability for expressing many parameters quantitatively that have been only qualitatively described in the past. Methods must be developed for quantifying variables such as particle shape, particle size distribution, and fabric. The variability of these properties must also be characterized in statistical terms. Special equipment and techniques must be developed to measure rapidly and accurately these basic properties in the laboratory. Such things as stress-strain curves from shear tests must be classified in terms of: strain at maximum shear stress, strain at failure, shape of curve, maximum shear stress, shear stress at failure, etc. Again, the variability must be known.

Once soils from specific lunar sites have been classified according to their basic properties and engineering behavior, the important variables that characterize differences in soil behavior between lunar sites can be established. Eventually it may be possible to find parametric relationships, such that given certain basic properties it is possible to predict the engineering behavior within certain bounds.

Thus, in the beginning, soil mechanics predictions must be based on engineering tests, while later predictions can be made on the basis of measurements of classification parameters such as porosity and fabric. (The ultimate goal being to develop the ability to measure the classification parameters by remote means.) To complement both types of predictions, a comprehensive program of site evaluation is required.

Site evaluation consists of three steps: 1) determining the engineering properties at a site and obtaining a prediction of the expected behavior under loads, etc.; 2) using instrumentation to measure the actual behavior; and 3) comparing the actual behavior with the prediction. Site evaluation is not only a guard against unexpected developments, but also is a check on our prediction capabilities. Appendix B indicates some of the problems that terrestrial soil engineers must face; the lunar soil engineer will confront these same problems, but without the vast experience that has been accumulated on earth. Site evaluation will provide the necessary experience.

3.1.3 Correlation Techniques

The ultimate engineering use of the correlation between material properties and soil behavior is to aid in selecting future sites and to design hardware for use under predictable conditions at future sites. Numerical correlations between soil properties and behavior have had some success on earth, particularly in local regions with fairly homogeneous profiles. Using the same rules for widely differing deposits has been less successful, although many "envelope predictions" have been effective.

Once a correlation is established between the classification parameters of lunar soils and the engineering behavior, the next step is to develop suitable techniques for determining the classification parameters by remote measurements; that is, to establish correlations between the classification parameters and the parameters of the remote measurement technique. Possible remote techniques are:

1. Geological inferences concerning material type and deposition;
2. Surface geometry determined by optical methods (such as crater dimensions);
3. Indirect measurements such as radio, radar, X-ray, radiation, temperature.

Some work has already been done along these lines but it has been hampered by three main difficulties: 1) not enough accurate data; 2) use of terrestrial models; and 3) most investigators have attempted to correlate engineering properties directly with remote data rather than go through the intermediate correlation with basic material properties. We feel that the data from the remote sensing devices actually reflect such basic properties as porosity and fabric rather than derived properties such as friction angle, ϕ, and cohesion, c (See Appendix B).

It should also be pointed out that not all correlation is numerical; correlation also involves "experience and judgment." The collection and processing of a great deal of data will allow lunar soil engineers to gain experience faster than has been possible on earth, since automated means of data collection and analysis for terrestrial soils have not received major attention until recently. This will aid not only in the selection of other sites but also in all other aspects of lunar soil mechanics.

3.2 ANALYTICAL RESEARCH

As described in Section 2.3, the solution of soil mechanics problems involves the prediction of initial stresses, changes in stresses and stress system and, for dynamic problems, the time history of loading. These quantities are predicted by elastic or elastic-plastic analyses in the case on non-failure conditions and by limiting equilibrium analysis for failure conditions.

In terrestrial analyses of both static and dynamic bearing capacity, settlement and slope stability, the most uncertain segment of the analysis generally concerns material properties and behavior data; i.e., the theory is better than our ability to determine the appropriate parameters. For these reasons, currently available and evolving analytical capabilities for solving these problems are sufficient. However, in some situations it may be necessary to obtain solutions for the boundary conditions peculiar to specific exploration hardware. A situation of this type is the rocket exhaust erosion problem where the analytical tools for solving the problem presently exist, but a solution for the particular boundary conditions does not.

Basic research in vehicle mobility may be necessary if the presently available terrestrial correlations cannot be applied to the lunar situation. The need for analytical research in mobility problems should be carefully considered in the light of Early Apollo observations and measurements.

3.2.1 Analytical Research on Foundation Problems

The static components of strength and compressibility are fairly well understood today, although the stress-strain compatibility of soils has not yet been adequately considered in terrestrial soil mechanics. In the past, for instance, settlement and bearing capacity have been calculated independently of one another without regard to their interdependence. Similarly, slope stability calculations neglect variations of strength with strain. If these could all be tied together our predictions of settlement and factors of safety would be more accurate and would permit more economical designs. Approximate methods that are sufficient on earth may not be satisfactory on the moon where the consequences of failure are catastrophic and improved methods of analysis may be necessary. The development of a finite-element computer program to account for the stress-strain behavior of soils under static conditions is, therefore, highly recommended.

The dynamic components of strength and compressibility still require much analytical work. All of these areas require laboratory studies to clarify the mechanisms involved and theoretical studies to improve our ability to make predictions of behavior. Weaknesses in the understanding of soil dynamics have already been recognized and research programs are underway at a number of institutions (Berkeley, University of Michigan, M.I.T.). These are fairly general studies, however, and specific studies directed toward landing and launch dynamics should be undertaken. The areas of dynamic settlement and dynamic slope stability are receiving adequate attention independent of NASA.

The specific area of landing dynamics has been studied previously for NASA. Good analyses have been made of the landing gear characteristics, but the study of soil-structure interaction has been limited primarily to model tests and simple analog comparisons. It is also necessary to investigate such factors as mode of failure and development of failure surface;

effects of footpad compressibility on soil strength; effects of ground motion on soil strength; variation of strength and compressibility parameters with cycles of stress and strain; etc.

3.2.2 Analytical Research on Mobility Problems

Mobility is a complex problem that has not yet yielded entirely to either experimental or theoretical research. It is based almost wholly on experience and judgment. This is not to say it cannot be solved: it just has not been solved yet.

Soil-vehicle interaction is an extremely complicated phenomenon, involving static and dynamic components of strength and compressibility. Even if it is theoretically solved, we can expect that variations in the soil type will necessitate very conservative designs. Thus, extensive theoretical studies of mobility are not recommended.

What is needed, rather, is to take the results of the tests on the lunar soil that will be conducted here on earth and to find a suitable material to model the lunar surface, one with similar strength and deformability characteristics. With these models it will then be possible to design lunar vehicles empirically before they are used on the moon. In the meantime, it will be necessary to be conservative in the design.

Also needed will be a trafficability study with statistical studies along these lines: stereo photographic analysis in terms of surface roughness and obstacles to determine optimum, alternate routes between two points. The optimization would be in terms of parameters for power consumption, time of traverse, points of interest along the way, exceptional hazards (such as rilles), complexity of navigation, etc. Of course, the analysis would be done by a computer into which would be fed a surface profile of the area surrounding the two end points. In the beginning such an analysis would neglect any differences in soil behavior; as soils data are accumulated and correlated they can also be included. This will be an invaluable aid in the latter part of the program involving the longer traverses.

REFERENCES

CONSTRUCTION

Office of the Chief of Engineers, Department of the Army, "Lunar Construction," Vols. 1 & 2, April 1963.

GENERAL

Baldwin, R.B., The Measure of the Moon, University of Chicago Press, 1963.

Branley, F.M., Exploration of the Moon, The Natural History Press, Garden City, New York, 1963.

Leondes, C.T., and R.W. Vance, Lunar Missions and Explorations, Wiley, New York, 1964.

NASA SP-88, "NASA 1965 Summer Conference on Lunar Exploration and Science," Falmouth, Mass., July 19-31, 1965.

Salisbury, J.W. and P.E. Glaser, ed., The Lunar Surface Layer, Academic Press, 1964.

LUNA IX

Gault, D.E., W.L. Quaide, and V.R. Oberbeck, "Luna 9 Photographs: Evidence for a Fragmental Surface Layer," Science, Vol. 153, No. 3739, August 26, 1966, pp. 985-988.

Jaffe, L.D., and R.F. Scott, "Lunar Surface Strength: Implications of Luna 9 Landing," JPL, TR 32-1003, July 22, 1966 (reprinted in Science, Vol. 153, No. 3734).

LUNAR SURFACE PROPERTIES

Gold, T., "Dust on the Moon," Vistas in Astronautics, Vol. 2, p. 261, Pergamon Press, New York, 1959.

Hibbs, Albert R., "The Surface of the Moon," Scientific American, Vol. 216, No. 3, March 1967.

Jaffe, L.D., "Depth and Strength of the Lunar Dust," Transactions, American Geophysical Union, Vol. 45, December 1964, p. 628.

Jaffe, L.D., "Strength of the Lunar Dust," Journal of Geophysical Research, Vol. 70, No. 24, December 15, 1965.

Jaffe, L.D., "Lunar Overlay Depth in Mare Tranquilitatus, Alphonsus, and Nearby Highlands," JPL TR 32-1021, 1966.

Jaffe, L.D., "Lunar Dust Depth in Mare Cognitum," Journal of Geophysical Research, Vol. 71, No. 4, February 15, 1966.

Jaffe, L.D., "Depth of the Lunar Dust," Journal of Geophysical Research, Vol. 70, No.24, December 15, 1966.

MODELS

Glaser, P.E., ed., "Studies of the Physical Characteristics of Probable Lunar Surface Materials," Air Force Contract No. AF 19 (628)-421 Proj. No. 8602, Task No. 860202, November 1964.

Halajian, J.D., "The Case for a Cohesive Lunar Surface Model," Grumman Research Department Report ADR 04-04-64.2, Grumman Aircraft Eng. Corp., Bethpage, New York, June 1964.

Hinners, N.W., "Lunar Surface Models and LEM Landing Dynamics," Bellcomm, Inc., Case 211, Task 11, September 30, 1965.

MODELS (continued)

Jaffe, L.D., "Bearing Strength of 'Fairy Castle' Structures," Journal of Geophysical Research, Vol. 70, No. 24, December 15, 1965.

Mason, R.L., W.M. McCombs, and D.C. Crambilit, "Engineering Lunar Model Surface" (ELMS), JFK Space Center, TR-83-D, September 4, 1964.

Nelson, J.D., "Laboratory Simulation of Lunar Surface Conditions," Submitted for Publication to the Journal of Environmental Sciences.

Weil, N.A., "Probable Soil Conditions on the Moon and Terrestrial Plants," First Intl. Conf. on the Mechanics of Soil-Vehicle Systems, Turin, Italy, June 1961.

ORBITER I

"Preliminary Terrain Evaluation and Apollo Landing Site Analysis Based on Lunar Orbiter I Photography," Langley Working Paper 323, November 4, 1966.

ORBITER II

"Preliminary Geologic Evaluation and Apollo Landing Analysis of Areas Photographed by Lunar Orbiter II," Langley Working Paper 363, March 1967.

RANGER VII

Gold, T., "Ranger Moon Pictures: Implications," Science, Vol. 145, p. 1046, 1964.

Kuiper, G.P., H.C. Urey, et.al., "Ranger VII, Part II. Experimenters' Analyses and Interpretations," JPL, TR 32-700, February 10, 1965.

RANGER VII (continued)

Schurmeier, M.L., "Ranger VII, Part I. Mission Description and Performance," JPL, TR 32-700, December 15, 1964.

RANGER VIII & IX

Kuiper, G.P., H.C. Urey, et.al., "Ranger VIII and IX, Part II. Experimenters' Analyses and Interpretations," JPL, TR 32-800, March 15, 1966.

Urey, H.C., "Observations on the Ranger VIII and IX Pictures," NASA Facsimile Reproduction of N66-31447.

SOIL MECHANICS (EXTRATERRESTRIAL)

Halajian, J.D., "Laboratory Investigation of 'Moon-Soils'," Grumman Research Department Report ADRO 4-04-621, Grumman Aircraft Eng. Corp., Bethpage, New York, May 1962.

Halajian, J.D., "Soil Behavior in a Low and Ultrahigh Vacuum," Grumman Research Department Report RE-197J, Grumman Aircraft Eng. Corp., Bethpage, New York, December 1964.

Halajian, J.D., J. Reichman, and L.L. Karafiath, "Correlation of Mechanical and Thermal Properties of Extraterrestrial Materials," Grumman Research Department Report RE-280, Grumman Aircraft Eng. Corp., Bethpage, New York, January 1967.

Hinners, N.W., "Lunar Soil Mechanics Information Derivable From Slope Analysis," Bellcomm, Inc., Case 211, June 25, 1965.

Jordan, D.W., "The Adhesion of Dust Particles," British Journal of Applied Physics, Supplement No. 3, S194.

SOIL MECHANICS (EXTRATERRESTRIAL)
(continued)

Lowe, H.J. and D.H. Lucas, "The Physics of Electrostatic Precipitation," British Journal of Applied Physics, Suppllement No. 2, S40.

McCarty, J.L., A.G. Beswick, and G.W. Brooks, "Application of Penetrometers to the Study of Physical Properties of Lunar and Planetary Surfaces," TN-D-2413, August 1964.

Mitchell, James K., "Current Lunar Soil Research," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 90, No. SM3, pp. 53-83, May 1964.

Nelson, J.D., "Environmental Effects on Engineering Properties of Simulated Lunar Soils," Ph.D. Thesis Illinois Institute of Technology, January 1967.

Roddy, D.J., J.B. Rittenhouse, and R.F. Scott, "Dynamic Penetration Studies in Crushed Rock Under Atmospheric and Vacuum Conditions," JPL TR 32-242, April 6, 1962.

Rowe, R.D., and E.T. Selig, "Penetration Studies of Simulated Lunar Dust," 7th Symposium on Ballistic Missile and Aerospace Technology, August 13-16, 1962.

Scott, R.F., J.D. Jaffe, et.al., "The Bearing Capacity of Simulated Lunar Surface in Vacuum," NASA Contract NAS 7-100, July 1963.

Scott, R.F., "Soil Mechanics Considerations in the Testing of Lunar Soil Models," in <u>The Lunar Surface Layer</u>, J.W. Salisbury and P.E. Glaser, ed., Academic Press, 1964.

Scott, R.F., "Lunar Problems in Soil Engineering," Journal Soil Mech. and Fdn. Div., ASCE, Vol. 91, No. SM1, pp. 1-14, January 1965.

Shaw, R., "Frictional Studies in Vacuum," SM Thesis, Mass. Inst. of Technology, May 1962.

SOIL MECHANICS (EXTRATERRESTRIAL) (continued)

Vey, E., and J.D. Nelson, "Studies of Lunar and Martian Soil Mechanics," IIT Research Institute Proj. No. M272, Phase III NASA-65(02), 1965.

Vey, E., and J.D. Nelson, "Engineering Properties of Simulated Lunar Soils," Jour. Soil Mech. and Fdn. Division, ASCE, Vol. 91, No. SM1, pp. 25-52, January 1965.

Vey, E., and J.D. Nelson, "Studies of Lunar Soil Mechanics," IIT Research Institute, Chicago, Illinois, May 1966.

Waters, R.H., "The Effect of Porosity on Shearing Resistance and Thermal Conductivity for Amorphous Soils in Vacuum," PhD Thesis, Texas A & M University, January 1967.

SOIL MECHANICS (TERRESTRIAL)

TRAFFICABILITY

Bekker, M.G., "Evaluation & Selection of Optimum Vehicle Types Under Random Terrain Conditions," GMC, Land Mobility Lab ER 61-107, April 1961.

Bekker, M.G., "Land Locomotion on the Surface of Planets," General Motors Corp., Defense Systems Division, Santa Barbara, California, paper 2015-61, American Rocket Society, October 9-15, 1961.

Haythornwaite, R.M., "Methods of Plasticity in Land Locomotion Studies," Proc. First Intl., Conf. on Mechanics of Soil-Vehicle Systems, Turin, Italy, June 12-16, 1961.

Hegedus, E., and R.S. Rowe, "Drag Coefficients of Locomotion Over Viscous Soils," JSMFD, ASCE, Vol. 86, SM2, April 1960, pp. 64-76.

TRAFFICABILITY
(continued)

Van Deusen, B.D., and C.H. Hoppe, "A Study of the Vehicle Ride Dynamics Aspect of Ground Mobility," Vol. 1: Summary; Vol. 1: Field Meas., WES, March 1965.

Waterways Experiment Station, "Trafficability of Soils: Development of Testing Instruments," T.M. NO. 3-240, Corps of Engineers, October 1948.

Waterways Experiment Station, "Studies of Aerial Cone Penetrometer: Field Tests," TR No. 3-462, U.S. Army Corps of Engineers, April 1958.

FOUNDATIONS AND SLOPE STABILITY

American Society of Civil Engineers, Conference on Stability and Performance of Slopes and Embankments, JSMFD, ASCE, Vol. 93, SM 4, July 1967.

Richart, F.E., Jr., and R.V. Whitman, "Comparison of Footing Vibration Tests with Theory," JSMFD, ASCE, Vol. 93, SM6, November 1967, p. 143.

Seed, H. Bolton, and G.R., Martin, "The Seismic Coefficient in Earth Dam Design," JSMFD, ASCE, Vol. 92, SM3, May 1966, p. 25.

Sherard, J.L., R.J. Woodward, S.F. Gizienski, and W.A. Clevenger, Earth and Earth-Rock Dams, Wiley, New York, 1963.

Spangler, M.G., "Culverts and Conduits," in Foundation Engineering, ed., G.A. Leonards. p. 965, McGraw-Hill Book Co. Inc., New York, 1962.

Terzaghi, K., Theoretical Soil Mechanics, Wiley, New York, 1948.

Terzaghi, K., and R.B. Peck, Soil Mechanics in Engineering Practice, Wiley, New York, 1967.

Whitman, R.V., and F.E. Richart, Jr., "Design Procedures for Dynamically Loaded Foundations," JSMFD, ASCE, Vol. 93, SM6, November 1967, p. 169.

SURVEYOR I

DuBridge, Lee A., "How the First 'Soft' Landing on the Moon was Achieved," Reader's Digest, December 1966.

Garba, J.A., "A Comparison of Some Predicted and Measured Variables For a Full-Scale Surveyor Drop Test," JPL, TR 32-1084, March 1, 1967.

Halajian, J.D., "Mechanical, Optical, Thermal and Electrical Properties of the Surveyor I Landing Site," Grumman Research Dept. Report AS 424-4, Grumman Aircraft Eng. Corp., Bethpage, New York, November 1966.

Hapke, B., "The Surveyor I and the Luna IX Pictures and the Lunar Soil," Cornell University, CRSR 253, October 1966.

Jaffe, L.D., R.F. Scott, et.al., "Surveyor I Mission Report, Part II, Scientific Data and Results," JPL, TR 32-1023, September 10, 1966.

SURVEYOR III

Scott, R.F., "The Feel of the Moon," Scientific American, Vol. 217, No. 5, p. 34, November 1967.

APPENDIX A

LITERATURE REVIEW

A review of the literature concerning the nature of the lunar surface layer has led to the following conclusions:

1. Most investigators tend to make very broad generalizations, seeking average values of density, friction angle, cohesion, etc., that can be applied to the entire surface. From an engineer's point of view this is futile; he must know the value of the various parameters at a given location or for a given situation. An average value of, say, density of the soil on the earth is not only useless but meaningless; the same is true on the moon. In the words of Urey: "... the process of the moon's origin was undoubtedly more intricate than anyone has the courage to imagine..." (Baldwin, p. 311).

2. In view of this tendency to "homogenize" the moon, it is likely that all of the investigators are correct to a degree concerning the properties of the lunar surface. Certainly the terrestrial surface is exceedingly complex and although surface moisture is apparently lacking on the moon, the lunar surface is nearly as complex. Thus, we should expect lava flows (as predicted by Baldwin, Urey, Kuiper, et.al.), deep layers of dust (Gold, Jaffe, Halajian), as well as coarse granular material of all sizes (Salisbury, Smalley). Furthermore, thse soil types are not limited to certain areas and can occur anywhere.

3. Remote prediction of surface properties is still in the development stage. No prediction of engineering behavior can be made at this time without tactile measurements. This is true on the earth and doubly true on the moon. The wide range of predicted properties amongst the investigators is

indicative of the status of remote measurements. From an engineer's point of view, he may as well disregard all photometric, radio, and radar data, as they are all invoked by the various investigators as evidence to support their hypotheses.

4. Very few competent soils engineers have been involved in the space program. Many experiments have been conducted that have proven things already known or that could have been predicted with the terrestrial soil mechanics available at the time. The research has shown an amazing lack of direction. The investigators have invariably begun with a preconceived idea of what the surface is like (on the "average"). They then find some evidence which seems to support their hypothesis; they either ignor conflicting evidence, or in explanation, propose some hitherto unheard of mechanism (without experimental support). Finally, they run tests on the supposed material, seemingly with the idea that the more data that is amassed, the more credible the model.

5. An engineering point of view is needed— one that is not trying to prove a theory concerning the origin and formation of the moon, but is attempting to solve engineering problems and increase the safety of men and equipment on the lunar surface.

I. INTRODUCTION

Before discussing the literature that was reviewed, it is enlightening to consider those aspects of the lunar environment which are of importance from an engineering point of view:

Meteorite Impact: the actual number is inversely related to the size - the smaller the size, the more numerous. An estimate of the average rate of infall: 1.3×10^{-14} $g/cm^2/sec$. (Salisbury and Smalley, 1964).

Seismic Activity: Estimated to be moderate (Baldwin, 1964).

Temperature: Large variation: -170°C to +110°C.

Pressure: Exact value has not been determined, but estimates of 10^{-10} to 10^{-12} torr frequently used.

Gravity: Only 1/6th that of earth.

All of these environmental aspects must be considered by the engineer. The last effect, the reduction in gravity, is probably the most important for we have the least experience with it; whereas, we already know quite a bit about low pressures, low temperatures, missile impact, and seismic activity.

The literature is full of mistaken impressions concerning the effect of gravity. For instance, one large firm, which has designed a roving vehicle for travel on the moon, expects the low gravity to smooth out what might be a bumpy terrestrial ride; while in fact, the vehicle will be much more unwieldy on the moon. In any dynamic situation in which accelerations are occurring (such as a vehicle or a machine), the relative acceleration is important, as well as the absolute acceleration.

Thus, on earth, if the maximum acceleration were 200 cm/sec^2, or only about 20% of gravity, the effect might be negligible. Put the same machine on the moon, and the acceleration is 120% of the lunar gravity - and the machine would leap off the ground and come crashing down again during each cycle. Similarly, the lesser gravity will adversely affect the control of a vehicle, not improve it.

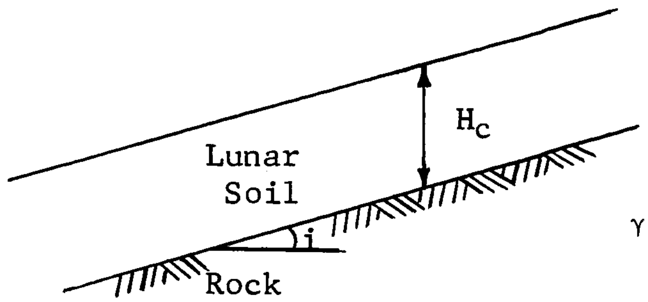
The reduced gravity also has special importance for soil mechanics. Before discussing this it is necessary to clear up a misunderstanding on the part of some soil engineers. A Commonly used unit of force among engineers is the kilogram, meaning the force equal to the weight (on earth) of a 1 kg mass. Now that engineers are investigating extraterrestrial situations, this type of unit has no place in the language. Rather, dynes or newtons must be used to avoid utter confusion. (1 dyne = 1 $gm\text{-}cm/sec^2$; 1 newton = 1 $kg\text{-}m/sec^2 = 10^5$ dynes = .225 lb). (This is not all their fault: countries employing the metric system also commonly use the kg as a unit of force).

Thus,

γ : nwt/m^3 - unit weight
ρ : g/cm^3 - mass density
c : nwt/m^2 - cohesion
ϕ : degrees - friction angle
Δq : nwt/m^2 - applied load
E : nwt/m^2 - modulus of elasticity

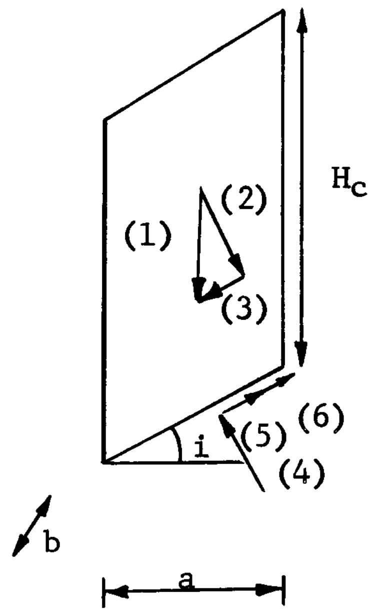
The first lunar samples will be tested on earth, rather than on the moon. If we use parameters measured on earth, it is necessary to modify the various formulas employed in soil mechanics.

1. Infinite Slope Stability



γ, c, & d measured on earth

Consider a slice (since infinite slope, side forces balance out)



Area: ab/cosi

On moon:

Forces: (1): $\frac{1}{6}$ γ ab H_c
(2): $\frac{1}{6}$ γ ab H_c cosi
(3): $\frac{1}{6}$ γ ab H_c sini
(4): $\frac{1}{6}$ γ ab H_c cosi
(5): $\frac{1}{6}$ γ ab H_c cosi tan ϕ
(6): cab/cosi

$\frac{1}{6}$ due to reduction of earth γ
cohesion is not reduced, as it is independent of gravity field.

Shears: (3): $\frac{1}{6}$ γ H_c sini cosi
(5): $\frac{1}{6}$ γ H_c $\cos^2$i tan ϕ
(6): $\frac{1}{6}$ c

For equilibrium:

$$\frac{1}{6}\ \gamma\ H_c \sin i\ \cos i = \frac{1}{6}\ \gamma\ H_c\ \cos^2 i\ \tan\ \phi + c$$

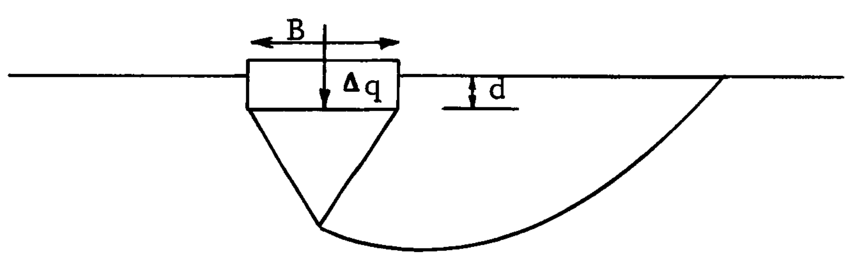
$$\frac{6c}{\gamma H_c} = \cos^2 i\ (\tan i - \tan\ \phi)$$

If we were analyzing a slope with these parameters on earth, the expression would be:

$$\frac{c}{\gamma H_c} = \cos^2 i\ (\tan\ i\ -\ \tan\ \phi)$$

Thus, we see one very important aspect of the reduced gravity on the moon: if the parameters are measured on the earth, the effect of the cohesion is six (6) times greater on the moon. However, if the parameters are measured on the moon, the factor of six (6) must be omitted from the equations.

2. <u>Bearing Capacity</u>



γ, c, ϕ, Δq measured on <u>earth</u>:

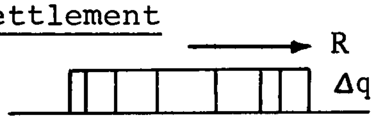
Then, on moon:

$$\frac{1}{6}\ \Delta q = \frac{1}{2}\frac{1}{6}\ \gamma B N_{\gamma} + cN_c + \frac{1}{6}\ \gamma d N_q$$

$$\Delta q = \frac{1}{2}\ \gamma B N_{\gamma} + 6\ cN_c + \gamma d N_q$$

Once more, the factor of 6 increases the importance of the cohesion. If $c = 0$, then the mass bearing capacity on the moon would be the same as on earth.

3. Settlement



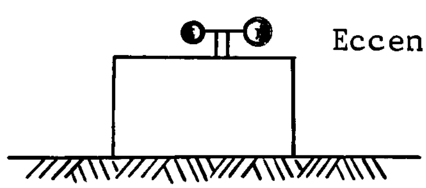
Δq and E measured on earth
μ: Poisson's Ratio

On moon: $$\rho = \frac{2(1 - \mu^2)\ \frac{1}{6}\ \Delta q R}{E}$$

$$\rho = \frac{(1 - \mu^2)\ \Delta q R}{3E}$$

E, like c, is independent of gravity field; thus, the settlement on the moon is $\frac{1}{6}$ that on the earth because of the reduced gravity.

4. Foundation Vibrations



Eccentric Masses

Frequency, amplitude, damping factor and acceleration are dependent on geometry, mass density, Poisson's ratio, and modulus of elasticity, all of which are independent of the gravity field.

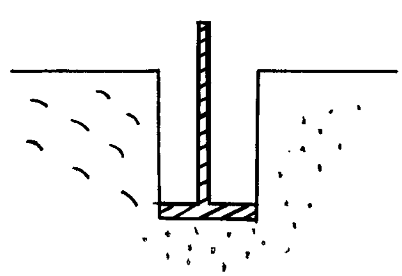
However, in the reduced gravity field of the moon, the accelerations become critical. An acceleration that would be acceptable on earth may cause the machine to leap off the surface of the moon, invalidating the basic assumptions in the theory. Such motion, of course, could not be tolerated.

Different investigators have proposed various values for the parameters used in the above analyses. Table A-1 presents a summary of the estimates that have been made. It can be seen that there is a wide difference of opinion among the investigators. Fig. A-1 indicates the range of values of bearing capacity that can be calculated from these parameters.

II. INDIVIDUAL INVESTIGATORS

J.D. Halajian

J. D. Halajian has supported a "deep, homogeneous underdense cohesive silicate" model of the lunar surface. A description of the reasoning that led him to this model is contained in "The Case for a Cohesive Lunar Surface Model," (1962). In this publication, Halajian was thinking in terms of loose, uncompacted soils, which would fail in compression, rather than shear:



However, he then called such a soil cohesionless, although it is impossible for a cohesionless soil to stand on a vertical cut. Later (1964), he cleared up that misunderstanding, and referred to his cohesive model (in which friction was negligible).

Halajian also ran tests in an airplane flying Keplerian trajectories and proved what could have been easily derived, as shown above in the section on Bearing Capacity. He also discussed the effect of gravity on porosity. It is never made clear whether he is discussing static or dynamic effects - but in either case, his experiments certainly did not model the lunar environment. The experiments consisted of depositing fine sand in water solutions of different densities, the idea being that the buoyancy of the water would model the effect of reduced gravity. Since the sediment volume was about the same for all the different solutions, it was concluded that gravity has no effect on porosity. This is an incorrect conclusion. Volume change is directly related to effective stress, and the effective stress is dependent on the gravity field. However, to explain Halajian's results:

1. Depositing soil in water is a common technique used to obtain the minimum density, or loosest condition, which depends primarily on the packing geometry. Since the soils would not get much looser in any environment, it is not surprising that the densities were essentially the same with the different fluids.

2. The effect of gravity on the surface, as far as compaction or consolidation is concerned would be negligible, since effective stresses are low already. At some depth, there would be an effect, depending on the overburden. However, in

these model tests, the soil column formed was so small that one would expect no measureable consolidation of the bottom of the sample (particularly since the soil was a fine sand).

3. From a dynamics point of view, the experiment again failed to model lunar soil deposition. On the moon, the soil particles would be falling into place - accelerating all the while. They would also tend to bounce rather highly again, densifying the underlying material. This model had a constant setting velocity and very little bounce, due to viscosity.

Halajian has relied rather heavily on photometric data which we have found to be far from conclusive. Furthermore, his estimates of density (ρ = 0.4 g/cm^3) and cohesion (c = 2.42 to 24.2 x 10^4 nwt/m^2) are based on radio and radar data, which is also doubtful. Finally, Halajian, as well as many others, have just too much faith in the thermal inertia constant, $\gamma = (k\ \rho c)^{-\frac{1}{2}}$. The idea is that if γ can be measured and c (specific heat) estimated, then either k (coefficient of thermal conductively) or ρ (mass density) can be estimated and the other parameter calculated. However, data even then indicated γ would vary from 350 to 1000 (cgs units). More recently, data from Surveyor I have indicated a range of γ between 250 and 1000. This points up the difficulty of finding "average" values of soil parameters.

Halajian (1964) also reported the results of an experiment intended to demonstrate cohesion of fine particles in high vacuum. Part of the experiment involved tumbling the particles to enhance degassing; however, we believe that this agitation built up an electric charge and caused the particles to stick to the container walls. The whole notion of vacuum cold welding of soil particles has been grossly exagerrated; in a later section, this will be discussed more fully.

Finally, in 1966, after the data from Surveyor I were made available, Halajian was still supporting a cohesive model. To match the Surveyor data, he has greatly increased his value of ρ (to $1 g/cm^3$) and decreased the value of c (to $10^4 nwt/m^2$). Nothing new was introduced by Halajian as evidence except for two minor observations: (1) the photographs are inconclusive concerning general or local shear of the soil beneath the footpads; from this, he concludes that the porosity = 60 to 70 %; (2) Radar measurements indicate a layer of lunar soil at least 1 foot thick with a dielectric constant of 1.8. This corresponds to a pure quartz at 70% porosity. Since the dielectric constant is extremely dependent on metallic content, the value of this observation is questioned; the radar data is also questionable.

R.F. Scott

R.F. Scott has been involved in both the Ranger and Surveyor programs at Jet Propulsion Laboratory. The material that the JPL group produces has been excellent, and is recommended reading.

In 1966, Scott and Jaffe attempted to evaluate the Luna IX landing. It was necessary to assume the depth of penetration of the probe; they took a very conservative value and as a result, the computed value of minimum bearing capacity is much less than that of other investigators.

In 1967, Surveyor III made a safe landing on the lunar surface and Scott was able to operate a scoop which probed the surface. The data from this experiment were not available in time for this report, but it is known that difficulties were encountered with the telemetry. Apparently, it was impossible to determine how much current was drawn by the motors operating the scoop. It is unfortunate that the data interpretation was thus complicated, as this was the most significant lunar soil mechanics experiment that has been performed to date. A similar experiment is planned for Surveyor VII.

L.D. Jaffe

L.D. Jaffe, like Scott, is associated with JPL, and has contributed some really excellent work.

In 1964, Jaffe attempted to determine the bearing capacity of the lunar surface from Ranger photographs of lunar slopes. He assumed that the specific gravity was 3.0 (the average for the moon and approximately that of common rock-forming silicates) and the porosity was 90% (based on photometric analysis). This resulted in a density of $.3 g/cm^3$. By analyzing observed slopes in the photographs, he was able to bracket values of ϕ and c. With these parameters, he was able to predict the minimum bearing capacity for a 0.1m and a 1m strip footing.

In 1965, he revised his figures and obtained an even smaller minimum bearing capacity (see Table A-1). Later data indicated that the assumed porosity was much too high and as a result, the bearing capacity is very conservative.

Recently (1966), Jaffe has been investigating the lunar dust depth, as suggested by the "soft" look of craters in the Ranger 7 photographs. To this end, model craters have been built onto which a layer of fine particles is deposited until a "match" is made between the model and the observed crater. The depth of dust cover is then estimated on the basis of geometric similarity; typically, this depth is 5m or more.

These experiments violate geometric similitude. The smallest particles used were only in the medium silt range and the largest particles were in the medium sand range. To use such large particles with respect to the diameter of the crater model is like considering the actual craters to be strewn with boulders 50 cm or larger in diameter.

Furthermore, Baldwin (1964) has found that isostatic adjustment is very important in changing the shape of craters. Thus, the observed "soft" look may be to a large extent due to this adjustment, rather than dust deposition.

SURVEYOR I

"Surveyor I Mission Report, Part II: Scientific Data and Results", (1966) is an excellent report and must be read to be appreciated. The photographs are magnificent and this publication contains the largest number that are readily available.

There is a great deal of information contained herein of general interest to engineers. The estimation of soil parameters is of particular interest to the soil engineer. However, no derivation is given to justify the results, which are as follows:

$$\rho = 1.5 \text{ g/cm}^3$$
$$\phi = 30° - 40°$$
$$c = 1 \text{ to } 4 \times 10^2 \text{ nwt/m}^2$$

From the Surveyor I photographs, we estimated a porosity of $n = 50 \pm 15\%$. Based on geologic considerations, we used a specific gravity, $G = 2.5$ to 3.0. These numbers lead to $\rho = 1.5 \pm .5 \text{ g/cm}^3$. Thus, we tend to agree with their value for the mass density.

Apparently, they arrived at ϕ and c by a very conservative approach. Since the footpad is in the shape of a truncated cone, the dynamic stress applied to the soil depends on the depth of penetration and can vary between a maximum and a minimum of 7×10^4 nwt/m^2 and 4×10^4 nwt/m^2, respectively. They chose the lower value, for D = 30.5 cm.

They also neglected the surcharge effect, which is unconservative. However, the very small depth of penetration (less than 8 cm) contributes only about 2% to the dynamic bearing capacity, which is equal to 3×10^3 nwt/m^2.

Finally, they assumed that the soil mass had failed in general shear. This is a very conservative assumption. The photographs were inconclusive in this respect. If the mode of failure had been local shear, then ϕ and c that were back-figured would have been much larger.

Thus, if one takes the ϕ and c predicted by JPL and uses N_γ, N_q and N_c (Terzaghi's bearing capacity factors) for the case of local shear, one arrives at comfortably conservative values of maximum bearing capacity (even as low as the observed static bearing pressure).

Note that given a value for bearing capacity, it is possible to back-figure an infinite number of combinations of ϕ and c. Based on experience with terrestrial soils, we agree with the range of ϕ values and the corresponding c values picked by JPL.

However, we cannot accept the equation used to describe the soil response: $F = C_1 + C_2 \cdot C_3 \left(\frac{dz}{dt}\right)^2$. Real soil is far more complicated. We consider attempting to evaluate the contants C_1, C_2, and C_3 as fruitless. They will undoubtedly not be constant.

Two further points are of interest:

(1) The Surveyor I report admits that the thermal inertia constant, γ, of the Surveyor I site can vary between a value of 250 to 1000 (cgs units). As mentioned earlier, such a large range precludes the usefulness of estimating "average" values of soil parameters.

(2) Based on an analysis of crater formation and composition, it was estimated that the observed material is vertically homogeneous on the order of 1m. deep. It is interesting to note that Salisbury and Smalley (1964) predicted this exact depth of rubble for marial regions, such as the Surveyor I site. JPL concluded that the underlying material may well be relatively strong rock; Salisbury and Smalley thought it might be indurated ash flows. Baldwin (1963) contends that the underlying material is lava flow.

T. Gold

T. Gold, from as early as 1955, has predicted that the great marial regions consist of deep layers of dust originating from the impact of metorites.

Apparently, his use of the word "dust" has caused great confusion. He uses "dust" to mean fine-grained material with cohesion; other investigators have interpreted "dust" to mean a material something like talcum powder. Be that as it may, when the photographs were obtained from the Surveyor I site, many investigators assumed the photos belied the Gold Model. On the contrary, Gold argued, the photos supported his model. (It is interesting to note that Halajian, who has argued against the Gold model, has used the exact same analogy as Gold; i.e., soft snow. As more datahave become available, the description of the models has come closer together, while the investigators have continued to criticize each other's model.)

B. Hapke

B. Hapke (1966), also of Cornell, ran a series of tests on a large area filled with cement. Fire crackers and dynamite sticks were exploded in the cement. When they were done, they had a perfect moonscape, complete with rimmed craters, rimless craters, piles of gravel-like rubble, "rocks", steep slopes, and linear features. The photographs must be seen to be appreciated.

Hapke (1964) earlier ran another interesting experiment that involved the consolidation of a rock flour. Assuming a lunar surface porosity of about 90% (ρ = .30 g/cm^3), it was found that at a depth of 10 cm, $\rho \cong$ .5 g/cm^3 and at 1 m, ρ = .8 g/cm^3. (It should be pointed out that very few basic soils tests such as this one have actually been run on proposed lunar soil models.)

Three problems are outstanding, however, in the Gold model. First, it is hard to imagine that absolutely every chunk of lunar rock was pulverized into dust due to meteorite impact. Surely there are rocks and boulders scattered throughout this mass of dust, if indeed there is that much dust. A rubble of highly variable particle size seems more likely.

Second, Gold is counting on the low velocity particles formed during meteorite impact to result in a soil structure of high porosity. Certainly the very top surface (which may be less than 1 cm some distance from a crater) will be loose, but the shock waves caused by impact must compact the soil significantly. Hapke's experiment with the cement confirms this: before the explosions, a man would sink into the cement over his ankles; afterwards, he would sink less than an inch.

Third, it is believed that Gold and the others are counting on too much cohesion between the particles comprising the dust. The one or two experiments that have been performed on fine-grained soils are far from conclusive.

Bromwell (1966) has shown that there is an increase in friction between quartz plates when the plates are exposed to a simulated lunar environment. No gross seizure or "cold welding" was observed. The explanation for this was that unlike steel, silicates are a brittle material and unable to flow plastically (except at very high normal stresses). It is possible that with very small particles there will be an increase in cohesion (after all, cohesion and friction are caused by the same mechanism: atomic bonding), but it is doubtful that there will be cold welding. In addition, the oft-quoted van der Waal's forces are probably very small. These forces are usually invoked when discussing clay-sized particles; most investigators speak of particles on the moon with a diameter of 10 microns (.01mm), which is well into the silt range. The coarsest clay particle is .002 mm and a medium particle .0003mm, or 5 to 30 times smaller than the expected lunar soil. The importance of the van der Waal's forces has thus probably been over-emphasized.

There is a need for good experimental work to actually measure increases in cohesion and friction in fine-grained soils due to the lunar environment.

There are other problems with the Gold Model of deep layers of dust, which will be discussed in the section on Baldwin.

<u>Salisbury & Smalley</u>

J.W. Salisbury and V.G. Smalley (1964), have presented a more conventional point of view concerning the composition of the marial surfaces. They feel the surface is a highly variable layer of rubble, mantled with a layer of highly porous dust.

By counting craters and computing the volume of rubble produced by the impact (mass of ejecta to mass of meteroid assumed to be 10^3), they were able to calculate the depth of the rubble, depending on distance from crater (95% of ejecta concentrated near crater). It is interesting to note that their computations of volume of material result in a depth of 1m or less on marias far from craters (see Surveyor I report), whereas Gold calculated the depth of dust to be a kilometer or more. (Note that Salisbury and Smalley go along with Gold's suggestion of electrostatic transport to account for movement of soil particles. On the other hand, they disagree with his idea that the dust is homogeneous; rather, the rubble is made up of highly variable and erratic particle sizes.) In the mountains, the rubble layer may be 1000m or more thick. Individual blocks of 4.5 m can be expected in the marias, and 10m to 22m blocks in the highlands. Just what is beneath the rubble, particularly in the marias is not known, but it might be indurated volcanic ash.

From a soil engineer's point of view, the Salisbury and Smalley model seems to be a reasonable description of what to expect on the moon. The soil profile is bound to be extremely complex and variable, both horizontally and vertically. One soil model cannot possibly work for all areas. For instance, Salisbury and Smalley predict that the dust layer could be quite thick in depressions, and thin on heights.

R.B. Baldwin

R.B. Baldwin has spent years analyzing data from the moon. The result has been two volumes of considerable stature: *The Face of The Moon* (1949) and *The Measure of The Moon* (1963).

The Measure of The Moon is a very detailed work, running over 470 pages. Because of the great detail, it is difficult to follow the thread of Baldwin's argument. But it is obvious that he has spent a great deal of time and effort in developing his thoughts. Instead of taking radio and radar data, etc., and predicting a model of the lunar surface, he has attempted to reconstruct the lunar geologic sequence of events - and he has done this in much greater detail then any other investigator. One thing stands out: Baldwin has suggested isostatic adjustment to account for "smoothing out" of old craters. This is a perfectly logical mechanism and would occur to a geologist immediately; but it was not mentioned in any of the other literature that was reviewed.

Baldwin's model of the lunar surface is a consequence of his assumptions regarding the moon's geologic history. In particular, he considers the marias to be filled with lava flows thousands of feet thick. He has not the slightest doubt that there is some dust and rubble everywhere, but not to the extent suggested by Gold (who holds that the maria are filled not with lava, but with dust). However, he made no attempt to predict the thickness of this rubble, nor its properties.

In fact, Baldwin disagrees very strongly with Gold's concepts: (1) Gold has stated that the marias are dark because the eroded rock (dust) is darker. Baldwin asks: If a ray crater is produced on the dark material and the dark material is composed of dust, why are the rays lighter than the dust? Certain data suggest that dust exists in the highlands- why are they bright instead dark? (2) Gold has used electrostatic transport to explain how dust has flowed into the maria from the highlands. Baldwin argues that a new contour map of the moon indicates that at least half the bright upland area drains not toward the maria, but toward the limb, and yet the limb is not dark. Furthermore, the great rill systems (which Baldwin takes to be evidence of surface tension due to cooling and collapse of marial lava; Gold neglects them),in general, mark the edges of the maria. How would the migrating dust cross these great trenches without filling them in? (3) Finally, Gold's source of marial dust is the eroded ruins of old craters. Baldwin considers that Gold has greatly over-estimated the amount of dust involved; and, in fact, isostatic adjustment is a much more reasonable explanation for the smoothing out of the features.

Baldwin and Gold are at two different extremes concerning the nature of the lunar surface. The correct model probably includes the best ideas of both.

TABLE A-1

ESTIMATES OF LUNAR SOIL MECHANICS PARAMETERS

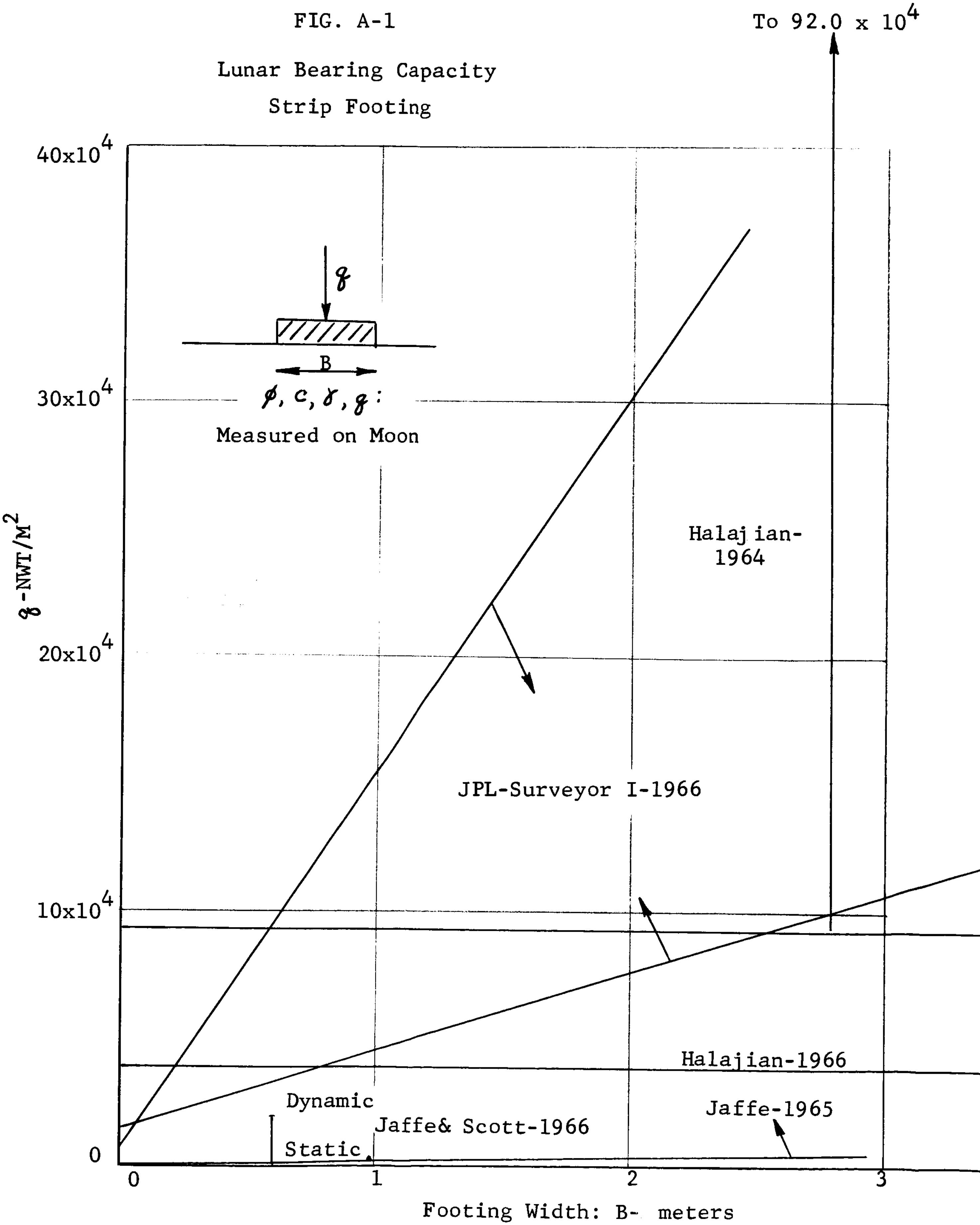
Source	ϕ	c (10^4 nwt/m^2)	Bearing Capacity 10^4 nwt/m^2)	ρ (g/cm^3)
Halajian-1964	0	2.42 to 24.2		0.4
Jaffe-1964			$\geq$ .049(B= 0.1m)	0.3
Jaffe-1965			$\geq$ .327(B= 1m)	
			$\geq$ .016(B= 0.1m)	0.3
			$\geq$ .163(B= 1m)	
Halajian-1966	0	1.0		1.0
Jaffe & Scott 1966			Static $\geq$ .05 (B=0.6m)	
			Dynamic $\geq$ 1 to 2 (B=0.6m)	
Luna IX -1966				1.0
JPL-Surveyor-I 1966	30° to 40°	0.013 to .04		1.5

No quantitative estimates have been made of the deformability of the lunar surface.

FIG. A-1

Lunar Bearing Capacity

Strip Footing



APPENDIX B

SOLUTIONS TO SOIL MECHANICS PROBLEMS

In soil engineering, we usually consider three broad areas of problems: stability, deformation, and fluid flow. It is expected that fluid flow through soils will play a small role in the early phases of lunar exploration and has thus been neglected in this report. In the later stages, it will become important in such activities such as waste disposal, fluid storage, etc. Even then, few new developments will be required as the theory governing fluid flow in porous media is far advanced. Determination of k, the permeability constant, will have to be according to standard laboratory techniques, as the available field methods are not readily adaptable to the lunar environment.

The areas of stability and deformation, although classically considered as two separate problems, may actually be considered together. In the past, deformations could be computed only so long as all of the stresses in the soil mass remained in the elastic range; i.e., there were no zones of plastic failure. At the other extreme, solutions for ultimate load were obtainable for cases of continuous plastic failure. But the load-deformation relationship between no failure and total failure could not be computed. Today, this gap is being closed and thus, we can now consider strength and deformation as parts of the same problem.

Soil is a particulate material, as opposed to a continuum. Because of its particulate nature it possesses frictional strength as well as cohesive strength. (Steel, concrete, wood, etc., are considered to have cohesive strength). This friction plays a very important role and has far-reaching effects on our theoretical solutions, as will be discussed below. The usual approximation for ultimate shear strength is that given by the Mohr-Coulomb envelope (Fig. B-1), where c = cohesion, which is a component of strength independent of normal stress; and ϕ = friction angle, which contributes a component dependent on normal stress. The envelope represents the maximum stresses which may be applied to a soil element to induce incipient failure. Thus, the element A with stresses as shown is just at failure whereas element B is not. We would say that A is in a plastic state and B is in an elastic state (by elastic, we do not mean the strict definition that requires that all strains be recoverable; we mean only that it is not plastic).

Another convenient representation of ultimate soil shear strength is the p-q envelope (Fig. B-2), where a is the cohesion and α is the friction angle, given by the relationships shown in Figure B-2. The Mohr-Coulomb envelope was constructed by drawing a line tangent to the Mohr's circle of stresses for elements at failure (such as A), while the p-q envelope was constructed by drawing a line through the tops of these circles. The two envelopes are geometrically related. It is only for convenience that we use one or the other envelope for a particular problem.

The in situ stresses for any soil element must lie below or on the envelope in the p-q diagram. For soil deposits which have been created by in situ weathering of rock, the stresses can be most anywhere in the region bounded by the envelope. For many of these deposits, the horizontal stress is greater than the vertical stress (element C, Fig. B-2). This occurs, for example, in dense sands or overconsolidated clays which have carried larger stresses in the past than the present overburden stress.

For soil deposits which have been created by transport and deposition of particles, the horizontal stress is given by $\sigma_h = K_o \sigma_v$, where K_o is the coefficient of lateral earth pressure at rest. This deposition is one-dimentional and involves compression of the soil without lateral strain. For normally consolidated soils (soils which are experiencing the greatest stress ever imposed right now), K_o is usually fairly constant and can be measured or approximated by $K_o = 1 - \sin \phi$. The "K_o -line" is shown in Figure B-2; element B is seen to lie on this line. For overconsolidated soils (soils which have experienced a greater stress in the past ($\bar{\sigma}_{vm}$) than now ($\bar{\sigma}_{vc}$) - usually caused by removal of over burden or desiccation), K_o is a function of the overconsolidation ratio (OCR), defined as $\bar{\sigma}_{vm}/\bar{\sigma}_{vc}$.

As an element of soil is stressed, it follows what is known as a stress path* from its in situ stresses to its final stresses; as it does so, it deforms due to shear and compression. Figure B-3 illustrates possible shear paths and Figure B-4 shows examples of stress-strain curves.

The solution of a strength-deformation problem, then, involves the following: (1) selection of representative elements in the soil mass for analysis; (2) determination of in situ stresses; (3) determination of stress path and final stress state; (4) sampling of representative soil samples;

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* Lambe, T.W., "The Stress Path Method," paper to be published in Journal Soil Mechanics and Foundations Division, ASCE, in January 1968.

(5) imposing the shear path on the samples and measuring the strain; (6) intergating the strains to determine the deformations. As long as no element in the soil fails, i.e., reaches the p-q envelope, accurate estimates of strain can be made. But as soon as a plastic zone is created, we have problems. Unfortunately, practically every situation of interest will involve some plastic flow. This includes: bearing capacity-settlement (if factor of safety is less than two to three, zones of plastic flow will develop); mobility; and slope stability.

The reason for the difficulty is that it has been impossible so far to adequately define a yield function for a frictional material. This is a fundamental gap in our knowledge and makes the theoretical analysis of soil far more difficult than that of steel or concrete. For $\phi = 0$ (purely cohesive materials), there are many solutions to stability problems based on the theory of plasticity. For positive values of ϕ, closed theoretical solutions are only available for weightless soils. Thus, even for the case of an ideal soil which has a stress-strain curve as shown in Figure B-5, and has ϕ, c, and γ greater than 0, there is no rigorous closed solution for bearing capacity, mobility, slope stability, etc. Furthermore, real soil is far from ideal. The stress-strain characteristics are dependent on: in situ stresses; stress history before achieving the in situ stresses; stress path during loading; loading rate, etc. Also, the Mohr-Coulomb envelope is actually curved for most soils, not a straight line. Added to this is the horizontal and vertical heterogeneity of soils that occurs even in so-called homogeneous deposits.

Finally, in many cases we are not even sure what the stress path is. Not that this has prevented engineers from developing methods of prediction in which they can have confidence. On the contrary, they have done quite well, considering. But it should be emphasized that much of this confidence is due to experience with the methods. Most of these methods are based on correlations which have been painstakingly developed. To use many of these methods on the moon may be a gross over-simplification.

Several tables have been prepared to summarize the role of soil mechanics in the lunar exploration program. Table B-1 presents the various situations on the moon that will involve soil mechanics and the solutions that are required. Table B-2 presents the analytical solutions which are now available. Table B-3 indicates how the various parameters are evaluated in terrestrial soil mechanics. As discussed in the main report, it is the determination of these parameters which will require the most effort; the theory is sufficiently developed for most applications. Many of the methods in Table B-3 will be inapplicable in the lunar environment; and conversely, methods which would not be considered on earth may offer the best solution on the moon. A primary function of the NASA Department of Soil Mechanics would be the development of methods to determine these parameters.

TABLE B-1

Lunar Situations Involving Soil Mechanics	Required Solutions: Static Settlement	Dynamic Settlement	Static Bearing Capacity	Dynamic Bearing Capacity	Dynamic Response	Static Slope Stability	Dynamic Slope Stability	Soil Technology	Others
Surface Contamination								X	
Landing	X	X	X	X	X	X	X		
Mobility		X	X	X		X	X		Trafficability
Laboratories-Machinery	X	X			X				
Observatories	X	X	X	X					
Excavations-Embankments						X	X		
Buried Structures									Soil-Structure Interaction
Spaceport	X	X	X	X	X	X	X		
Tunneling-Mining									Rock Mechanics
Soil Stabilization								X	

TABLE B-2

Required Solutions	Analytical Solutions Now Available	Required Parameters
Static Settlement	<u>Total; Time-Independent:</u>	γ, K_o
	In Situ Stresses: $\sigma_v = \int_0^H \gamma\, dz$, $\sigma_H = K_o \sigma_v$ (Both can be wrong in tectonic regions)	
	Applied Stresses:	
	(1) Isotropic Homogeneous Linearly Elastic Halfspace	μ
	(2) Elastic Layers (Not in convenient form yet)	E, μ
	(3) Consideration of Elastic-Plastic Nature of Soil (Highly simplified; only for special cases)	σ - ϵ
	(4) Statistical (Brand new)	
	Settlement-Along Center Line:	
	(1) Lab Tests to Measure Strain to Calculate E and to Substitute Into Equations to Calculate Displacements	
	(2) Lab Tests to Measure Strain; Displacement= $\int_0^H \epsilon\, dz$. Lab tests may or may not take into account (calculated) field stress path; much difficulty when near failure.	

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
	<u>Differential; Time-Independent:</u>	
	Same as "Total" except with respect to a corner or edge.	
	Disagreement as to what constitutes "allowable" differential settlement.	
	Off ¢ $\sigma_1 \neq \sigma_v$ and $\sigma_3 \neq \sigma_H$: know that soil behaves differently under rotation of principal planes, but little data.	
	<u>Total; Time-Dependent:</u>	
	Amount: (1) Oedometer: $\rho = \int_0^H \frac{C_c}{1+e_0} \log \sigma_f / \sigma_i \, dz + \int_0^H C_\alpha \, dz$	C_c, e_0, C_α
	(2) Triaxial: E and μ into equations.	E, μ
	(3) Triaxial: $\rho = \int_0^H \epsilon \, dz$	
	Rate: (1) Primary: $\frac{t_F}{t_L} = \frac{H_F^2}{H_L^2}$ (only one dimension)	C_v
	(2) Secondary: $C_\alpha = \frac{\Delta H}{H} / \Delta \log t$	
	<u>Differential; Time-Dependent:</u>	
	Uses values of parameters from above. (Work being done on two and three dimensional consolidation)	

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
Dynamic Settlement	<u>Total; Time-Independent:</u>	
	Stresses: Same as static	γ, K_0, μ
	Settlement: Cyclical lab tests to measure accumulation of strains : $\rho \int_0^H \epsilon_A \, dz$	f
	<u>Differential; Time-Independent:</u>	
	Same	
	<u>Total; Time-Dependent:</u>	
	Same	
	<u>Differential; Time-Dependent:</u>	
	Same	
Static Bearing Capacity	<u>Shallow Foundation:</u>	
	(1) Terzaghi: $q_{ULT} = \alpha \frac{1}{2} \gamma B N_\gamma + \beta c N_c + \delta q N_q$	ϕ, c, γ
	Drawbacks:	
	(a) Minimum of Σ moments assumed = Σ min. moments	N_γ, N_c, N_q
	(b) Neglects strength of surcharge	
	(c) Assumed failure surface	α, β, δ
	(d) ϕ and c are complex function of stress system	

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
	(e) Empirical corrections: (1) Footing shape (2) Inclination and eccentricity (3) Local shear vs. general shear (f) Factor of safety ≥ 3 (Despite all this, extremely powerful tool) (2) Highly porous "dust" (porosity $\geq$ 50%)-Halajian $\gamma_{ULT} = (N_S \frac{z}{D} + N_c) \frac{f(e)}{d}$	N_S, N_c
	Drawbacks: (a) Particles assumed to be spheres-d (b) Constant γ with depth (c) Final porosity must be specified (d) f(e)-"surface tension": data variable (e) Large factor of safety	$f(e)$, γ, G
	<u>Deep Foundation:</u> Piles: (1) Empirical rules based on resistance to driving (2) Load tests (meaningless in soils characterized by time dependent behavior) Caissons: (1) Experience (2) Bearing capacity equations	

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
Dynamic Bearing Capacity	"Live" Load: Factor of safety times estimated load due to people and equipment	
	Machines: (1) Stresses analyzed according to static theory (2) Computer program for considering load-deformation when have local zones of failure.	
	Impact: (1) No increase in bearing capacity until acceleration $\geq 10g$. (2) Cratering experiments with missiles being conducted.	
Dynamic Response	<u>Halfspace:</u> Isotropic, Homogeneous Linearly Elastic Halfspace	
	(1) Rigid base or parabolic stress distribution	
	(2) Modes: (a) Vertical (b) Torsional (c) Horizontal	
	(3) Geometry + soil density= Amplitude @ resonance Damping ratio DLF @ resonance	Geometry γ, μ
	(4) (3) + shear wave velocity= Resonant frequency Acceleration @ resonance	E, μ

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
	Mass-Spring-Dashpot: (1) Modes: (a) Vertical, horizontal, torsional, etc. (b) Vertical-horizontal coupled (2) Must know: (a) Density (b) Spring constant (critical) (c) Damping ratio	 γ k D
Static Slope Stability	(1) Taylor: Friction Circle (max.& min. F.S.) and charts (2) Fellenius: Slices (different parameters) $F.S. = \frac{\Sigma[\bar{c}\Delta x \sec\alpha + \bar{N}_i \tan\bar{\phi}]}{\Sigma W_i \sin\alpha}$ (fallen from favor) (3) Modified Bishop (slices): $F.S. = \frac{\Sigma[\bar{c}\Delta x + (W_i - u_i - \mu_i \Delta x)\tan\phi]\frac{1}{M_\alpha}}{\Sigma W_i \sin\alpha}$ (4) Bishop $M_\alpha = \left(1 + \frac{\tan\phi \tan\alpha}{F.S.}\right)\cos\alpha$ (5) Morgenstern-Price (must specify failure surface, but may be any shape) (All methods are two dimensional, i.e., plane strain; however, methods are far more powerful than the data deserves)	ϕ, c, γ ϕ, c, γ, u ϕ, c, γ, μ

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
Dynamic Slope Stability	(1) Constant Acceleration: Extra forces added to static solution	k
	(2) Varying Acceleration (such as earthquake):	
	(a) Assume an equivalent static acceleration	k
	(b) Cohesionless soils in infinite slopes (must determine what constitutes critical deformation)	ϕ, γ
	(c) Dynamic Seismic Coefficient	k
Soil Technology	<u>Surface Contamination:</u> Soil Technology has a good record of explaining the "why" of soil behavior, but it has never been successful in predicting the behavior in advance. In addition: Disagreement concerning: (a) Mineralogy and fabric of lunar soil (b) Pressure and composition of lunar atmosphere (c) Temperatures @ surface	
	<u>Stabilization:</u> Pure trial and error (real problem is application under vacuum conditions)	

TABLE B-2 (cont.)

Required Solutions	Analytical Solutions Now Available	Required Parameters
Mobility	Hard Soil: Dynamic analysis of terrain Subjective analysis of human response	$\mathcal{C}, n$
	Soft Soil: (1) Cone Index: The resistance to penetration of a standard cone has been correlated with trafficability.	
	(2) Bekker's Equations: Semi-empirical-theoretical approach; must evaluate a series of parameters.	$c, \phi, k_1, k_2, k_c, k_\phi, n$
Soil-Structure Interaction	<u>Buried Structures</u>	
	Elasticity Closed Solutions Finite-Element Computer Programs	γ, E, μ
	Plasticity Marston and Spangler	γ, ϕ
Rock Mechanics	<u>Tunneling-Mining:</u> (1) Experience (2) Mechanics of Jointed Rock	

TABLE B-3

Required Parameters

Parameter	Test	Comments
γ - Unit weight γ = Weight/Volume γ_w = Unit wt. of water	(1) Undisturbed samples (a) Clays (b) Sands above water table (c) Sands below water table (2) $\gamma = \frac{G+Se}{1+e}\gamma_w$	Thin wall tubes pushed into soil; capillarity permits sampling; injections; freezing of pore water (very complicated) Only if G (specific gravity), S (degree of saturation), and e (void ratio) are known.
K_o - Coefficient of lateral earth pressure at rest $K_o = \bar{\sigma}_H / \bar{\sigma}_V$	(1) Oedometer (2) $K_o \approx 1 - \sin\bar{\phi}$ Experimentally observed for sands and NC clays (3) $K_o = (1 + \frac{2}{3}\sin\bar{\phi})\tan^2(45 - \frac{\bar{\phi}}{2})$ Theoretically derived for sands and NC clays (4) $K_o = \frac{\mu}{1-\mu}$	$\bar{\sigma}_H$ Measured with transducer (best) $\bar{\phi}$ at maximum obliquity Only NC $K_o \approx .9(1 - \sin\bar{\phi})$ Only NC Theory of Elasticity
μ - Poisson's Ratio $\mu = \varepsilon_H / \varepsilon_V$	(1) Triaxial Shear: Drained (2) Undrained	Not constant with strain (many other factors - see E) Water incompressible: $\mu = 1/2$
E- Young's Modulus $E = \frac{1}{\varepsilon_z}[\sigma_z - \mu(\sigma_x + \sigma_y)]$	Static (1) Triaxial Shear $E = \Delta\sigma_V / \varepsilon_V$	E is a very complex function of: Stress level (strain) OCR Anisotropy

TABLE B-3 (cont.)

E- Young's Modulus (cont.)	(2) Oedometer $E = \frac{\Delta\sigma_v}{\varepsilon_v}\left(1 - \frac{2\mu^2}{1-\mu}\right)$ (3) Isotropic Consolidation $E = \frac{\Delta\sigma_v}{\varepsilon_v}(1 - 2\mu)$ (4) Empirical: $E = CS_u$	Strain rate Aging Thixotropy Stress System Stress History Density Difficulty is to find C and S_u (undrained strength)
	Dynamic (5) In situ shear wave velocity	$v_s = \sqrt{G/\rho}$; $E = 2(1+\mu)G$
	(6) Plate bearing; small vibrators	Difficulty extrapolating
	(7) Subgrade modulus	Defined only in terms of soil type
C_c- Compression Index $C_c = \frac{\Delta \log \bar{\sigma}_c}{\Delta e}$	(1) Oedometer	Standard
	(2) Triaxial	Not generally used, but not difficult.
e_o- Initial Void Ratio	(1) Back-figured from γ (2) Gas-expansion method	
C_α- Coefficient of secondary consolidation $C_\alpha = \Delta H/H \, \Delta \log t$	(1) Oedometer	
C_v - Coefficient of consolidation	(1) Oedometer (2) Triaxial	Always too low: neglect horizontal drainage, sand seams, etc.

TABLE B-3 (cont.)

Parameter	Test	Comments
ϕ - Friction Angle and c- Cohesion Intercept	(1) Triaxial (2) Direct shear (3) Simple shear (4) Torsional shear (5) Cylindrical shear (6) Back-figure from in situ tests (Bearing capacity)	ϕ and c are influenced by all the factors which affect E. Difficult to intercept data
S_u - Undrained Shear Strength	(1) Vane shear (2) Unconfined Compression (3) Undrained triaxial (4) Undrained direct shear (5) Undrained simple shear (6) Undrained torsional shear (7) Undrained cylindrical shear	Takes the place of C in an undrained stability analysis (bearing, slope, mobility, etc.); ϕ is set= 0 S_u is influenced by all the factors which affect E.
N_γ, N_c, N_q - Bearing Capacity Factors (Terzaghi)	Theoretical Functions of only $\bar{\phi}$	Two solutions for local shear and general shear
D - Damping Ratio $D = \frac{\delta}{\delta_{CR}}$; $\delta_{CR} = 2\sqrt{kM}$	(1) Halfspace Theory (2) $D = \frac{.85}{\sqrt{1-\mu}\sqrt{b}}$ (3) Dynamic Triaxial	Only important near resonance

TABLE B-3 (cont.)

k - Coefficient of Acceleration (Dynamic slope stability)	(1) Empirical (2) Elastic response of embankment	No rational method to select value; typically: .1 g to .5 g Requires computer solution
c, n - Constants defining frequency distribution of a terrain	Measured in field	Many types of Profilometers Photography and radar
k_1, k_2 - Stress-strain parameters (Mobility)	Measured in situ	Empirical correlations
k_c, k_ϕ, n - Deformation parameters (Mobility)	Measured in situ	Empirical correlations

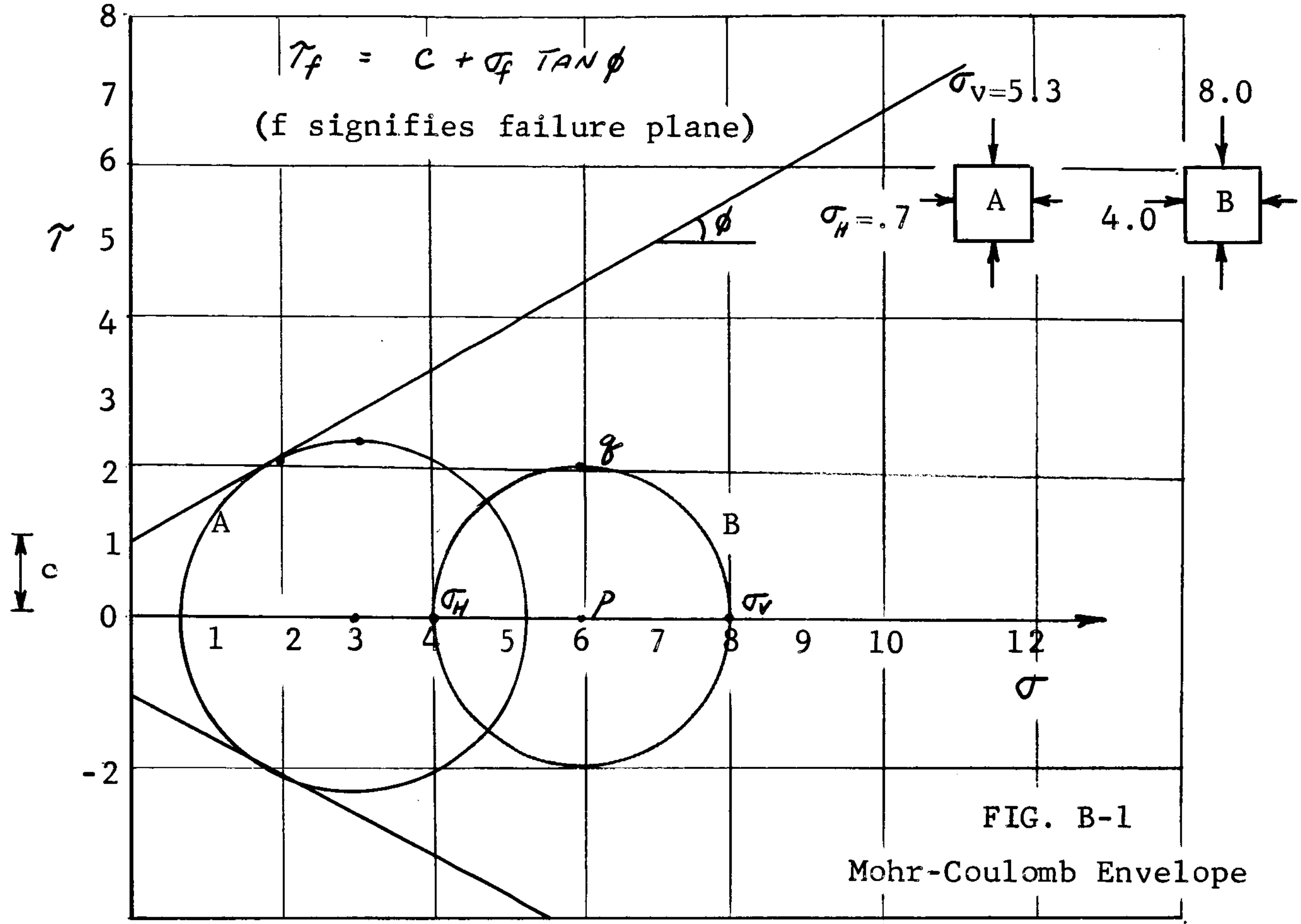


FIG. B-1

Mohr-Coulomb Envelope

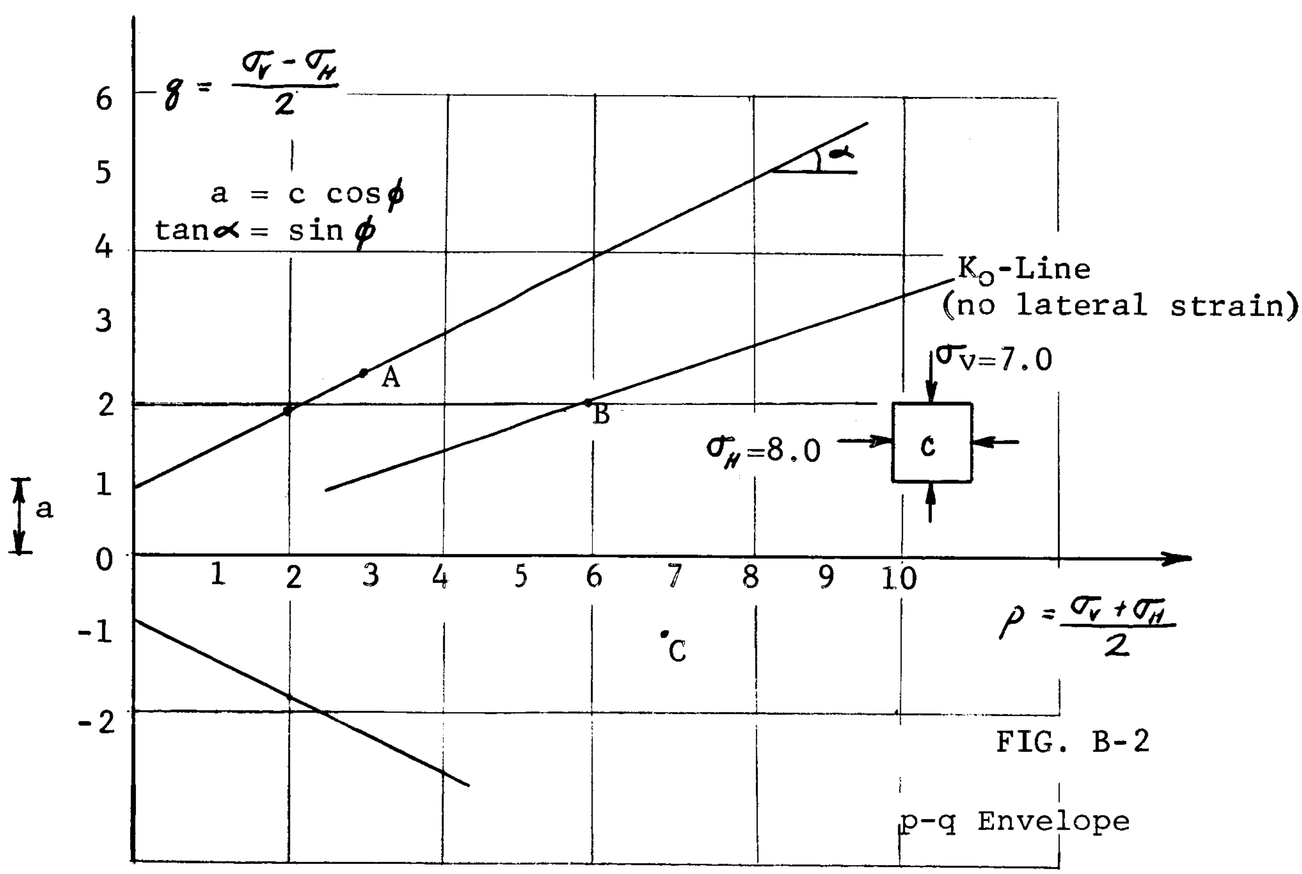
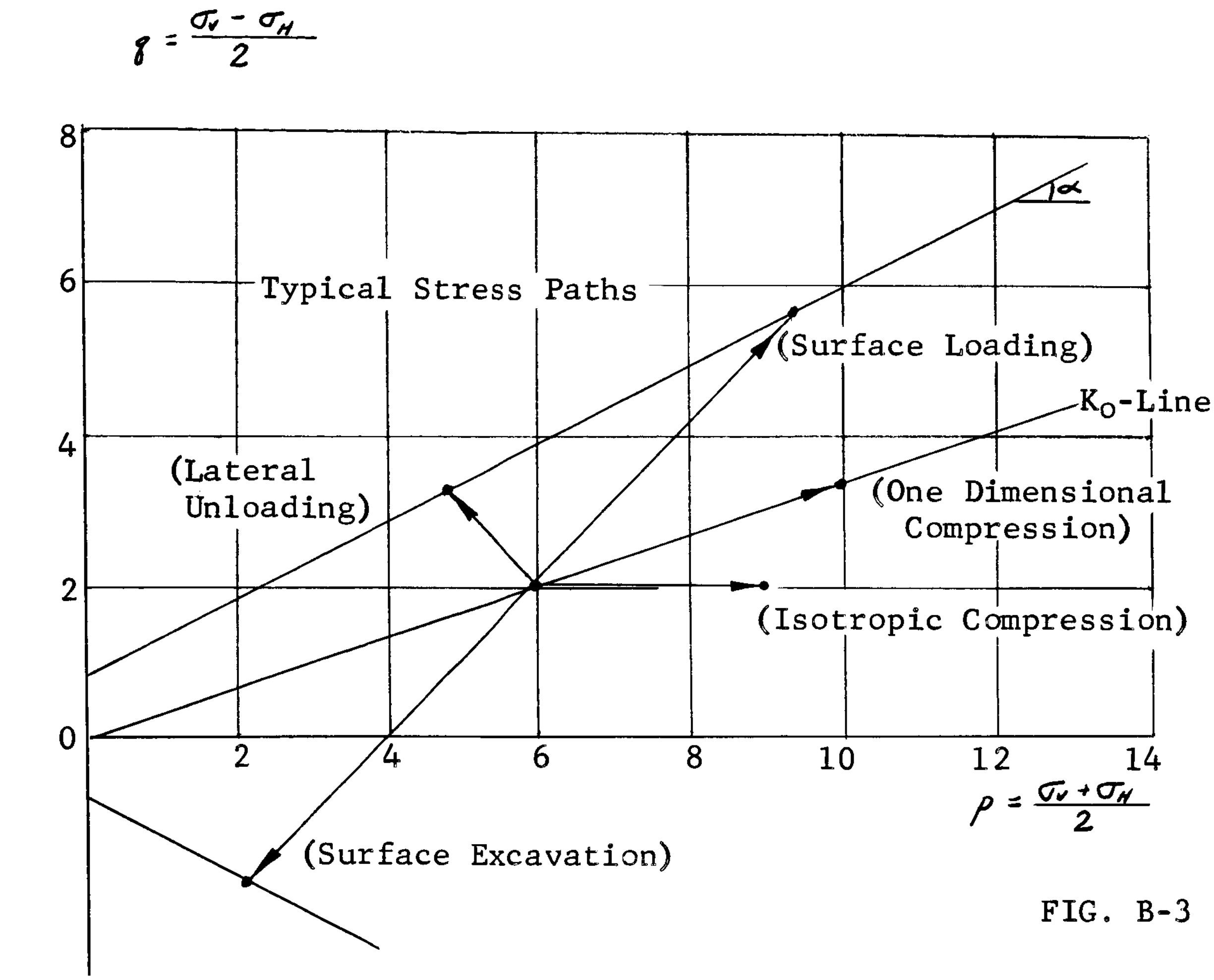


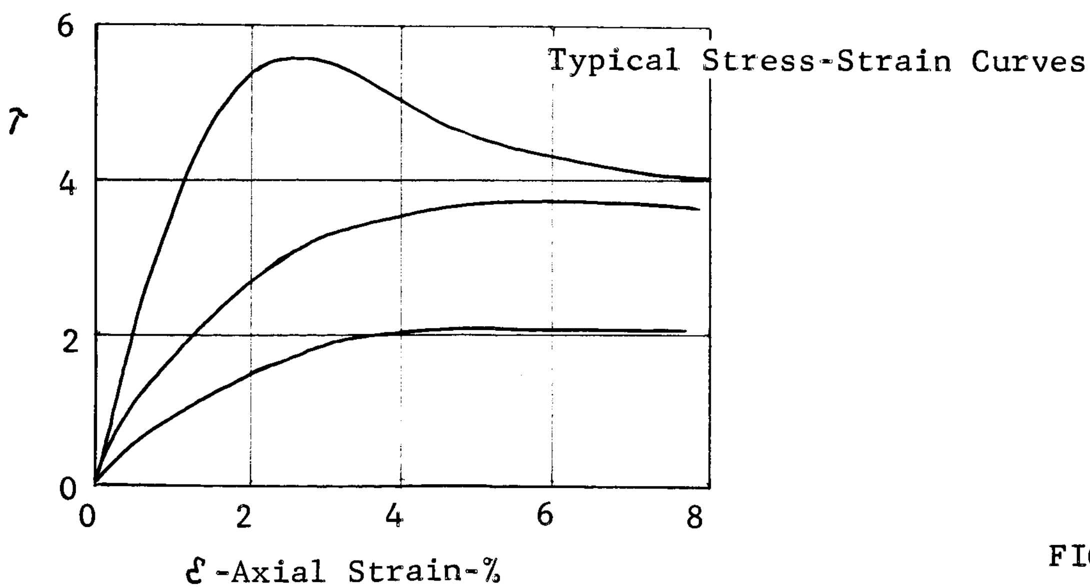
FIG. B-2

p-q Envelope



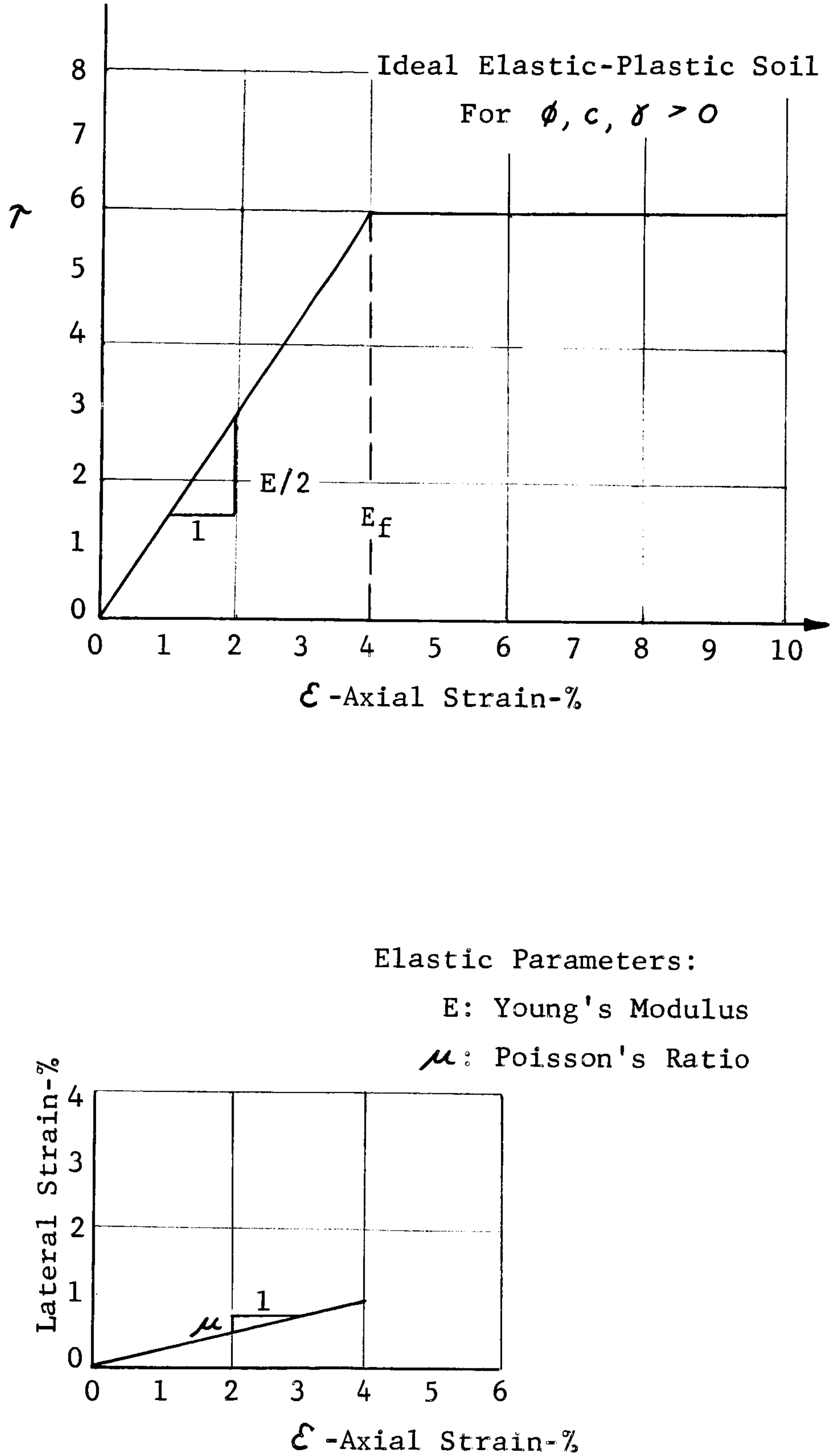
$q = \frac{\sigma_V - \sigma_H}{2}$
8
6
4
2
0
Typical Stress Paths
(Surface Loading)
K_O-Line
(Lateral Unloading)
(One Dimensional Compression)
(Isotropic Compression)
(Surface Excavation)
2
4
6
8
10
12
14
$p = \frac{\sigma_V + \sigma_H}{2}$

FIG. B-3



τ
6
4
2
0
Typical Stress-Strain Curves
0
2
4
6
8
ε -Axial Strain-%

FIG. B-4



Ideal Elastic-Plastic Soil
For $\phi, c, \gamma > 0$
τ
E/2
1
E_f
ε -Axial Strain-%
Elastic Parameters:
E: Young's Modulus
μ: Poisson's Ratio
Lateral Strain-%
1
μ
ε -Axial Strain-%

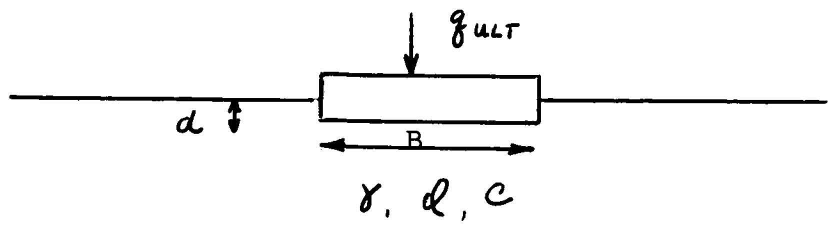
FIG. B-5

APPENDIX C

EXAMPLES OF SOIL MECHANICS SOLUTIONS

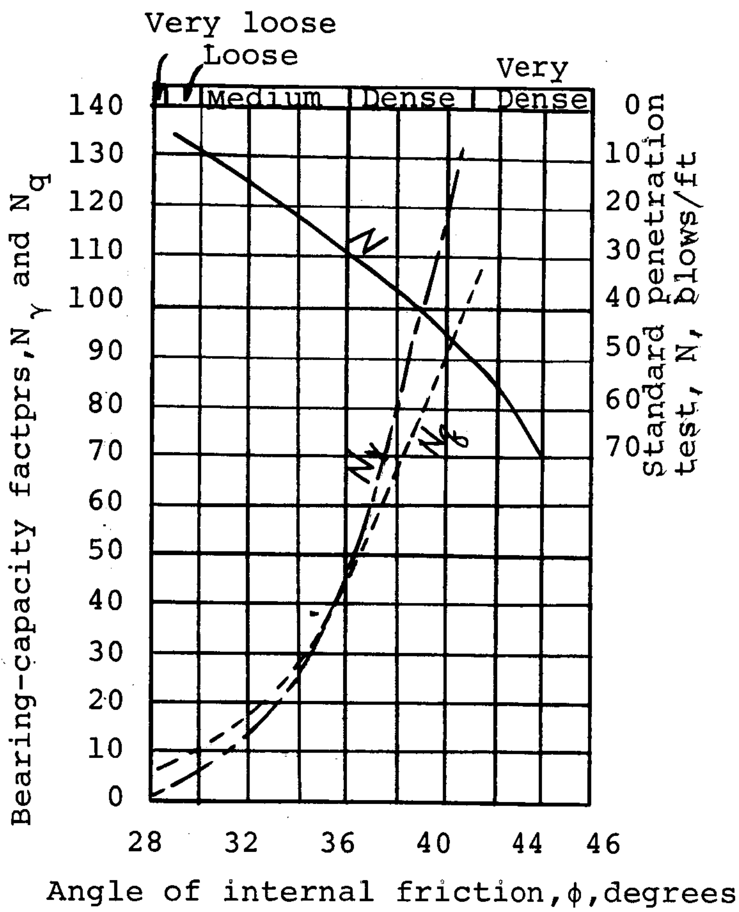
Examples taken from Soil Mechanics, by T. William Lambe and R.V. Whitman, John Wiley, New York, 1966 Preliminary Edition

Bearing Capacity



$$q_{ult} = \frac{1}{2}\ \gamma B N_\gamma + cN_c + d\gamma N_q$$

N_γ, N_c & N_q: Functions of ϕ



(From Peck, Hansen and Thornburn, 1953)

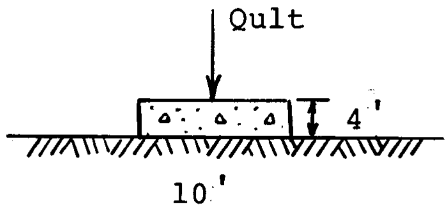
Fig. 1 BEARING CAPCITY FACTORS WHICH AUTOMATICALLY INCORPORATE ALLOWANCE FOR LOCAL SHEAR FAILURE

EXAMPLE 1 - Footing on Ground Surface

Given: Footing as shown

Find: Qult

Solution:



$\phi = 30°$

$\gamma = 120$ pcf

$$N_\phi = \frac{1 + \sin\phi}{1 - \sin\phi} = 3$$

$$N_\gamma = \frac{1}{2}\left[\,15.60 - 1.73\,\right] = 6.94$$

$$N_q = 3^2 = 9$$

$$\frac{Qult}{B} = (\Delta q_s)_u = (120)\ (10)\ \left(\frac{6.94}{2}\right) = 4160 \text{ psf}$$

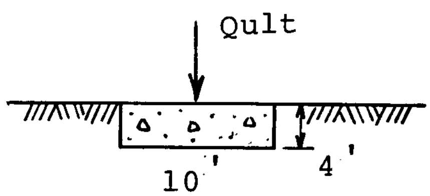
Qult = 41,600 lbs. per foot of wall

EXAMPLE 2 - Shallow Buried Footing

Given: Footing as shown

Find: Qult

Solution:



$\phi = 30°$

$\gamma = 120$ pcf

$$\frac{Qult}{B} = (\Delta q_s)_u = 4160 + (120)\ (4)\ (9)$$

$$= 4160 + 4320 = 8480 \text{ psf}$$

Qult = 84,800 lbs. per foot of wall.

EXAMPLE 3 - Shallow Buried Footing

Given: A wall which is 7 ft. wide at the base, and which rests 3 ft. below the surface of a sand with $\phi = 35°$ and $\gamma = 110$ pcf.

Find: Bearing capacity.

Solution: From Fig. 1 we find:

$$N_\gamma = 35 \qquad N_q = 34$$

Hence:

$$(\Delta q_s)_b B = \frac{1}{2}\ (110)\ (7)^2\ (35) + (110)\ (7)\ (34) = 94{,}000 + 78{,}000$$

$$= 172{,}000 \text{ lb per ft. of wall.}$$

EXAMPLE 4 - Plate Bearing Test

Given: A plate bearing test shows a bearing capacity failure at a bearing stress of 3.6 tons/ft^2. The plate is 1 ft square and bears 3 ft below the ground surface. The unit weight of the soil is estimated at 100 pcf.

Find: Bearing capacity for a footing 6 ft square, to be founded 3 ft below ground surface.

Solution: The first step is to find a value of ϕ which will satisfy Equ. (1):

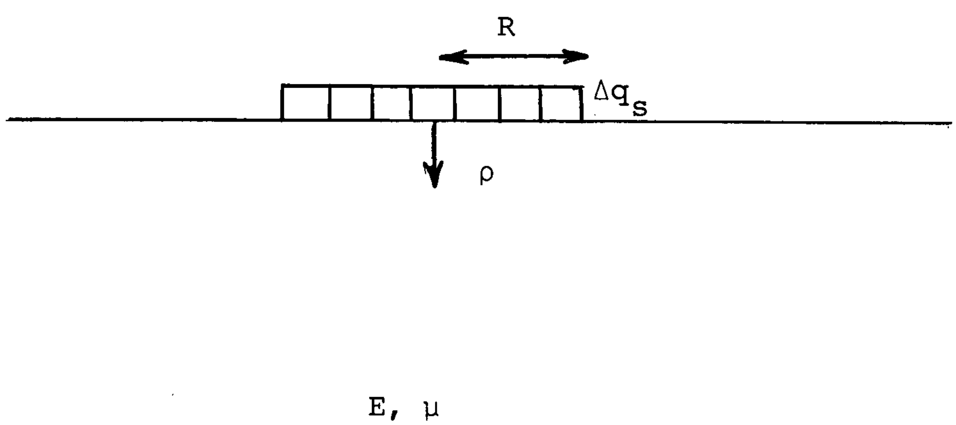
$$2000\ (3.6)\ \text{psf} = \frac{1}{2}\ (100)\ (1)\ N_\gamma + 3\ (100)\ N_q$$

After several trials, it is found that $\phi = 33°$, giving $N_\gamma = 18$ and $N_q = 21$, satisfies the equation. Now these values of N_γ and N_q can be applied to the actual footing:

$$(\Delta q_s)_b = \frac{1}{2}\ (100)\ (6)\ (18) + 3\ (100)\ (21)$$

$$= 11{,}700\ \text{psf or}\ 5.85\ \text{tsf}$$

SETTLEMENT



Equ. (1): $\rho = \Delta q_s \dfrac{2R}{E} (1-\mu^2)$

EXAMPLE 1 - Tank on Elastic soil

Given: A tank loading with $D = 153\frac{1}{4}$ ft and $\Delta q_s = 5.5$ kip/ft^2. $E = 2000$ kips/ft^2 and $\mu = 0.45$.

Find: The settlement at the center of the tank for the condition of homogeneous, isotropic soil of infinite depth.

Solution:

$$\rho_{\text{℄}} = \Delta q_s \frac{R}{E} 2 (1 - \mu^2) \qquad \text{Equ. (1):}$$

$$\Delta q_s = 5.50 \text{ kips/ft}^2$$

$$R = \frac{D}{2} = \frac{153\frac{1}{4} \text{ ft}}{2}$$

$$\rho_{\text{℄}} = \frac{5.50 \dfrac{\text{kips}}{\text{ft}^2} \times \dfrac{153\frac{1}{4} \text{ ft}}{2} \times 2\,(1-0.45^2)}{2000 \text{ kips/ft}^2}$$

$$= \underline{\underline{0.346}} \text{ ft} = \underline{\underline{4}} \text{ inches}$$

Settlement may be estimated by multiplying an average strain times the depth of the bulb of stresses. The following tabulation shows several ways in which this might be done.

Assumed Depth of Bulb	Average Strain	Settlement (inches)
3R = 230 feet	Use strain at depth of 3R/2: $\varepsilon_v = 0.00106$	3.0
4R = 306 feet	Use strain at depth of 2R: $\varepsilon_v = 0.00076$	2.8

The first method, using a bulb of depth 3R, gives an estimate close to the actual result of 4 inches.

EXAMPLE 2 - Tank on Sand

Given: A 48 ft high tank is built on an infinite deposit of sand with:

$$\gamma = 129 \text{ pcf}; \quad \mu = 0.45.$$

Find: The settlement of the center of the tank when filled with water for the following conditions:

1. D = 100 ft; E constant and equals 4,000 kips/ft^2
2. D = 200 ft; E constant and equals 7,000 kips/ft^2
3. D = 100 ft; E varies as σ_{vo} and equal to 4,000 kips/ft^2 at d = 75 ft.
4. D = 200 ft; E varies as σ_{vo} and equals 4,000 kips/ft^2 at d = 75 ft.
5. D = 100 ft; E varies as $\sqrt{\sigma_{vo}}$ and equals 4,000 kips/ft^2 at d = 75 ft.
6. D = 200 ft; E varies as $\sqrt{\sigma_{vo}}$ and equals 4,000 kips/ft^2 at d = 75 ft.

Solution:

$$\rho = \Delta q_s \frac{R}{E} 2 (1 - \mu^2)$$

$$\Delta q_s = 48' \times 62.4 \text{ lb/cu ft} = 3.0 \text{ kips/ft}^2$$

$$1. \ \rho = 3.0 \text{ kips/ft}^2 \times \frac{50 \text{ ft} \times 1.60}{4000 \text{ kips/ft}^2} = 0.60 \text{ ft}$$

$$2. \ \rho = \frac{3.0 \times 100 \times 1.60}{4000} = 1.20 \text{ ft}$$

EXAMPLE 2 (contd)

3. Since E varies as σ_{vo} and σ_{vo} varies as depth, E varies as depth. Take "average point" at depth = $\frac{3}{4}$ D. $E_{\frac{3D}{4}} = E_{75} = 4{,}000$ kips/ft^2

   ρ for case 3 same as for case 1, i.e., $\rho = 0.60$ ft.

4. $\rho = \dfrac{(3.0)(100)(1,6}{2 \times 4{,}000} = 0.60$ ft.

5. ρ case 5 same as ρ case 1, i.e., $\rho = 0.60$

6. $\rho = \dfrac{(30)(100)(1.60)}{\sqrt{\frac{150}{75} \times \frac{\gamma}{\gamma}} \times E \text{ at } 75} = \dfrac{(3.0)(100)(1.60)}{\sqrt{2} \times 4{,}000} = 0.85$ ft

BEARING CAPACITY- SETTLEMENT

EXAMPLE 1 - Footing on Sand

Given: A round, rigid footing resting on sand with: $\phi = 34\frac{1}{2}°$

$\gamma = 100$ lb/cu ft, $\mu = 0.45$

Find: Relationship among D (varying from 1 ft to 10 ft), ρ and $(\Delta q_s)_b$ for:

1. E = 200 kips/ft^2
2. E = 200 kips/ft^2 at depth 10 ft and varying as σ_{vo}
3. E = 200 kips/ft^2 at depth 10 ft and varying as $\sqrt{\bar{\sigma}_{vo}}$

Solution: Bearing Capacity: $(\Delta q_s)_b = (0.6)\frac{1}{2}\ \gamma\ DN_\gamma + \gamma dN_q$

from Fig. 1, $N_\gamma = 30$

$(\Delta q_s)_b = (0.6)\ (\frac{1}{2})\ (100)\ D\ (30) = 0.9\ D$ in kips/ft^2

Settlement: $\rho = \Delta q_s\ \frac{R}{E}\ \frac{\pi}{2}\ (1 - \mu^2)$

$$\frac{\pi}{2}\ (1 - 0.45)^2 = (\frac{\pi}{2})\ (.797) = 1.25$$

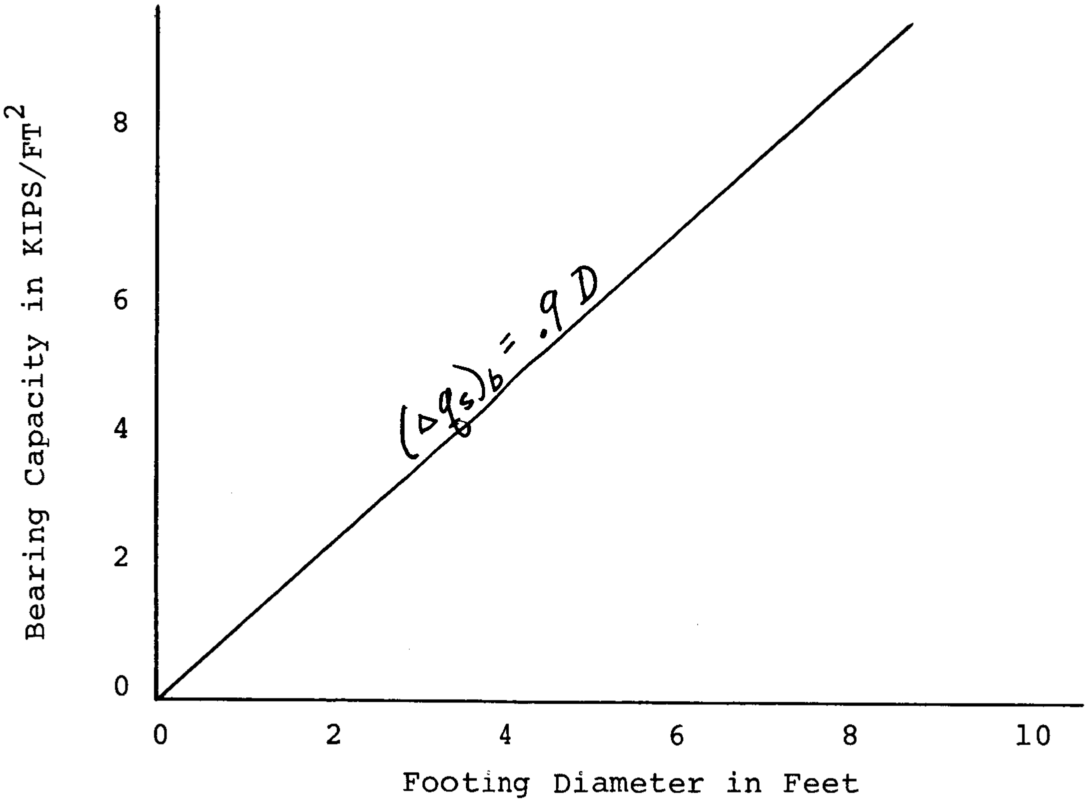
Case 1: $\rho = \Delta q_s\ R\ \frac{1.25}{200} = \Delta q_s R(6.25 \times 10^{-3})$

Case 2: $\rho = \Delta q_s\ R \frac{1.25}{\frac{(200)}{10}\frac{(3R)}{2}} = \Delta q_s\ (4.17 \times 10^{-2})$

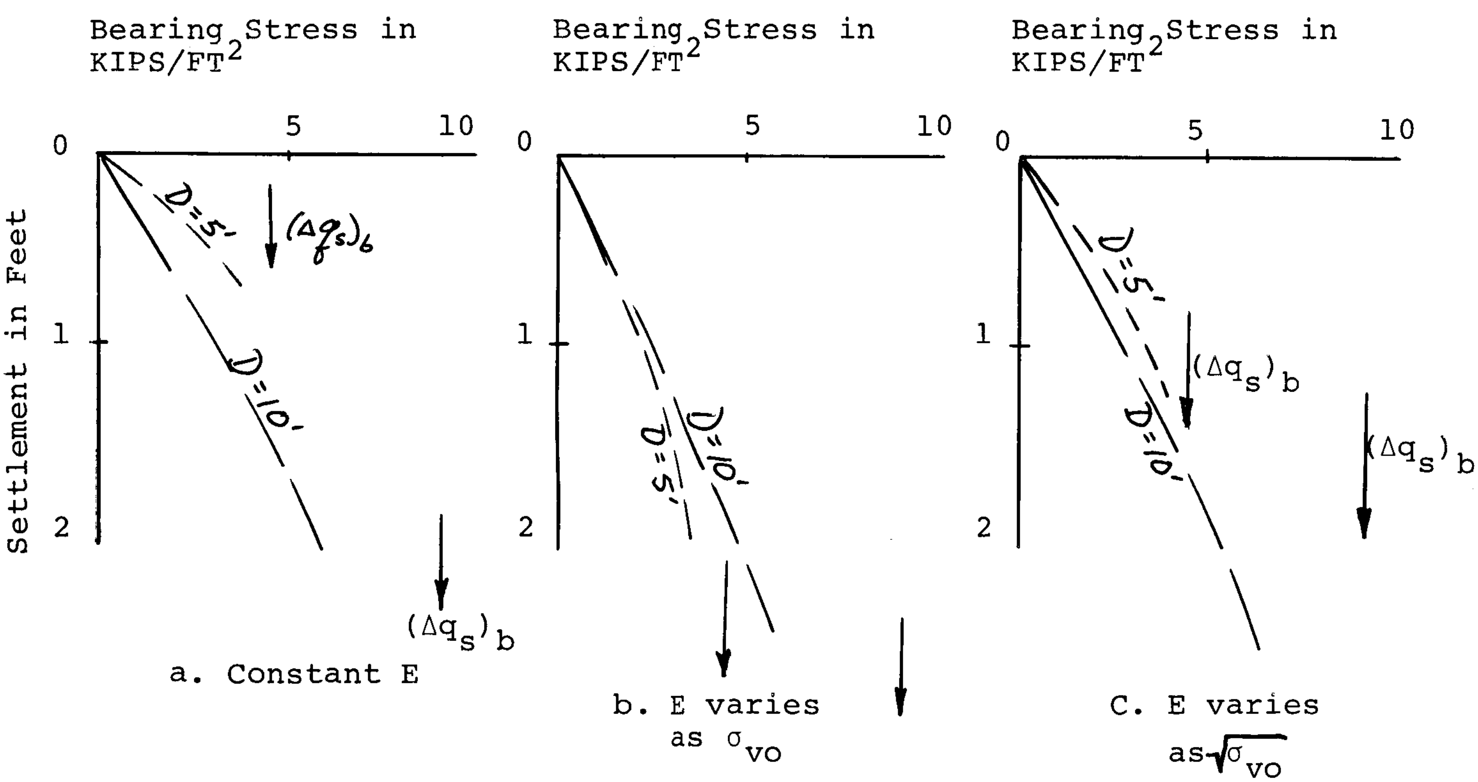
Case 3: $\rho = \Delta q_s\ R\ \frac{1.25}{(\frac{200}{\sqrt{10}})\sqrt{\frac{3}{2}\ R}}\quad \Delta q_s\ \sqrt{R}\ (1.62 \times 10^{-2})$

EXAMPLE 1(contd.)

		D = 5 ft	D = 10 ft
$(\Delta q_s)_b$	=	4.5 $kips/ft^2$	9.0 $kips/ft^2$
Case 1:	ρ for $\Delta q_s = 3$	-	.0938 ft
	ρ for $\Delta q_s = 1\frac{1}{2}$	.0235 ft	.0469 ft
Case 2:	ρ for $\Delta q_s = 3$	-	.125 ft
	ρ for $\Delta q_s = 1\frac{1}{2}$	.063 ft	.063 ft
Case 3:	ρ for $\Delta q_s = 3$	-	.109 ft
	ρ for $\Delta q_s = 1\frac{1}{2}$	.038 ft	.054 ft



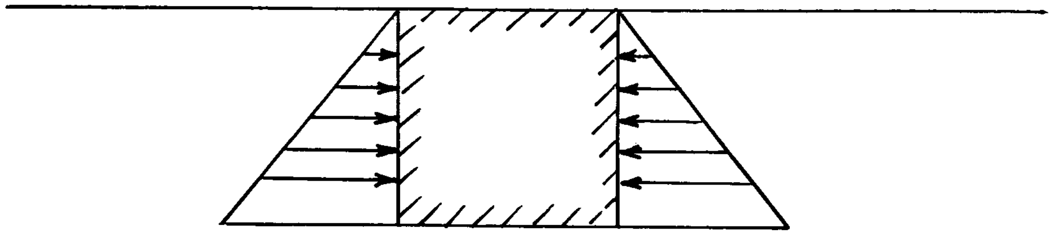
Bearing Capacity in KIPS/FT^2
0
2
4
6
8
$(\Delta q_s)_b = .9D$
0
2
4
6
8
10
Footing Diameter in Feet

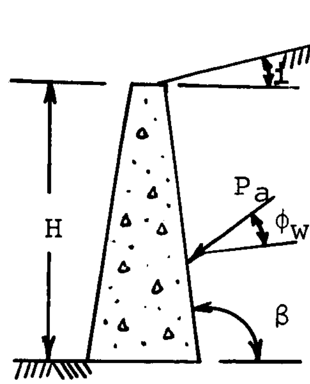


Bearing Stress in KIPS/FT^2
Settlement in Feet
0
1
2
5
10
D=5'
D=10'
$(\Delta q_s)_b$
a. Constant E
b. E varies as σ_{vo}
C. E varies as $\sqrt{\sigma_{vo}}$

EXAMPLE 1

EXCAVATIONS





$$P_a = \frac{1}{2}\gamma H^2 \left[\frac{\csc\beta \, \sin(\beta-\phi)}{\sqrt{\sin(\beta+\phi_w)}+\sqrt{\dfrac{\sin(\phi+\phi_w)\sin(\phi-i)}{\sin(\beta-i)}}}\right]^2$$

FIGURE 1 COULOMB EQUATION FOR SLOPING BACKFILL AND WALL FRICTION

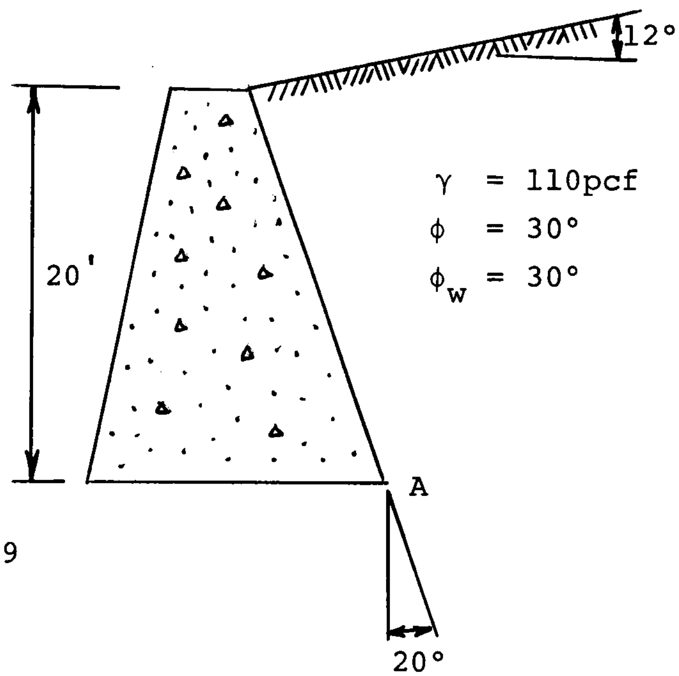
	i =	-30°	-12°	±0	+12°	+30°
φ=20°	β′ = +20°		0.57	0.65	0.81	
	β′ = +10°		0.50	0.55	0.68	
	β′ = +0°		0.44	0.49	0.60	
	β′ = -10°		0.38	0.42	0.50	
	β′ = -20°		0.32	0.35	0.40	
φ=30°	β′ = +20°	0.34	0.43	0.50	0.59	1.17
	β′ = +10°	0.30	0.36	0.41	0.48	0.92
	β′ = ±0°	0.26	0.30	0.33	0.38	0.75
	β′ = -10°	0.22	0.25	0.27	0.31	0.61
	β′ = -20°	0.18	0.20	0.21	0.24	0.50
φ=40°	β′ = +20°	0.27	0.33	0.38	0.43	0.59
	β′ = +10°	0.22	0.26	0.29	0.32	0.43
	β′ = ±0°	0.18	0.20	0.22	0.24	0.32
	β′ = -10°	0.13	0.15	0.16	0.17	0.24
	β′ = -20°	0.10	0.10	0.11	0.12	0.16

β'=β-90°

For $\phi_w = 0$

FIGURE 2 COEFFICIENT OF ACTIVE STRESS AS FUNCTION OF INCLINATION OF WALL AND BACKFILL

EXAMPLE 1



Given: Retaining wall* and backfill as shown.

Find: Moment of active thrust about point A

Solution using Fig. 1

$i = 12°$

$\beta = 110°$

$\csc 110° \sin 80° = \dfrac{\sin 80°}{\sin 70°} = 1.049$

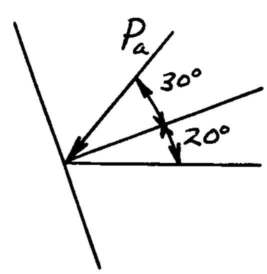
$\sqrt{\sin 140°} = 0.803$

$\sqrt{\dfrac{\sin 60° \sin 28°}{\sin 98°}} \quad \sqrt{\dfrac{0.866 \text{x} 0.470}{0.990}} = 0.641$

$Pa = \frac{1}{2}(110)(20)^2 \left[\dfrac{1.049}{0.803 + 0.614}\right]^2 = 22{,}000(0.528) = 11{,}600$ lb/ft

Horizontal component of Pa

$= P_a \cos 50° = 7450$ lb/ft



P_a acts 1/3 of way up wall, or at vertical distance of 6.67 ft above base.

Moment of Pa about point A = 7450(6.67) = 49,800 lb ft/ft

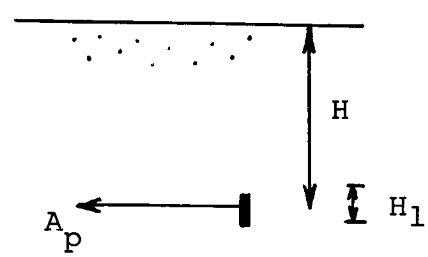
* Or buried instrument.

Approximate solution using Fig. 2

Use Ka for $\phi_w = 0$, but incline Pa at $\phi_w = 30°$ to normal to wall.

Ka = 0.59 instead of 0.528 above, so that moment is over-estimated by 12%.

EXAMPLE 2 - Buried Anchor Plate



$$A_p \cong q_{ult} = \frac{1}{2} \gamma B N_\gamma + cN_c + d \gamma N_q \text{ (Bearing Capacity Equation)}$$

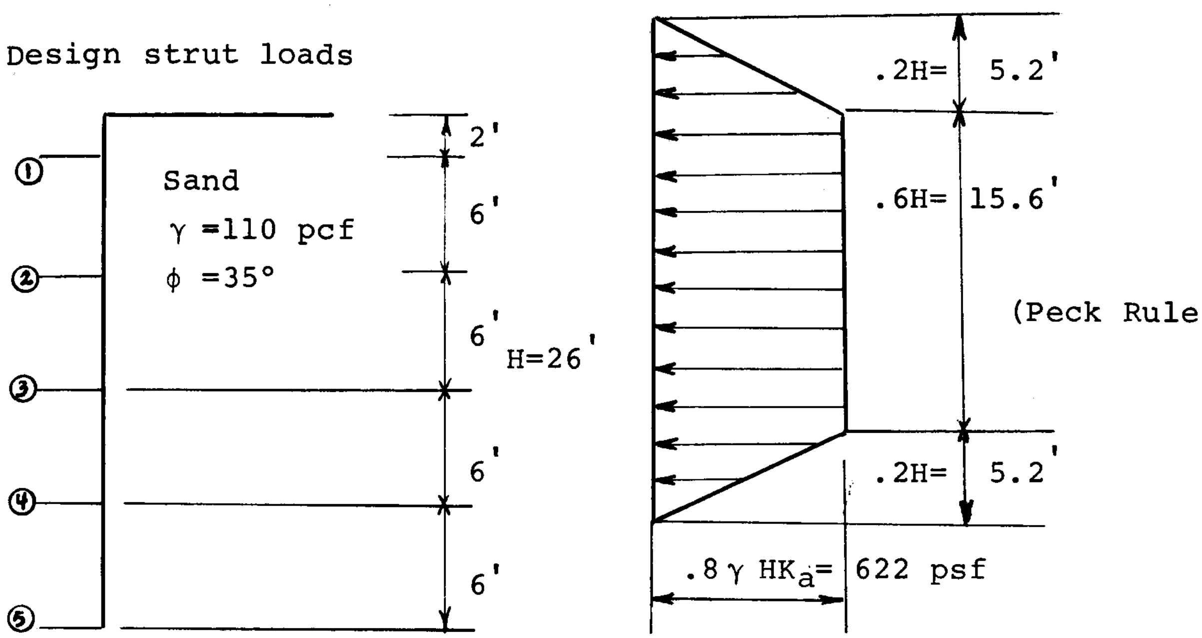
$$= \frac{1}{2} \gamma H_1 N_\gamma + cN_c + (H - \frac{H_1}{2}) \gamma N_q$$

EXAMPLE 3 - Braced Cut in Sand (Peck Rule)

Given: Excavations and bracing system as shown

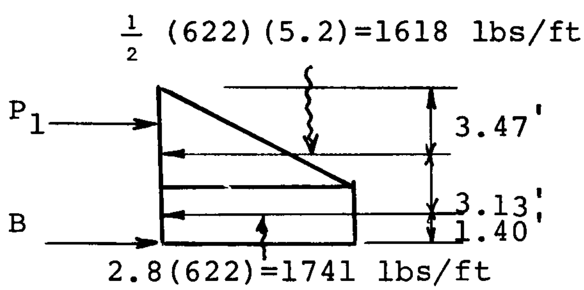
Find: Design strut loads

Solution:



From Fig. 1: Ka = 0.272 (β =90°; ϕ_w = 0°; i =0°)

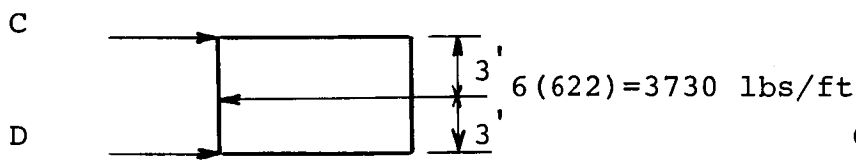
Maximum stress is: (0.272)(110)(26)(0.8) = 622 psf



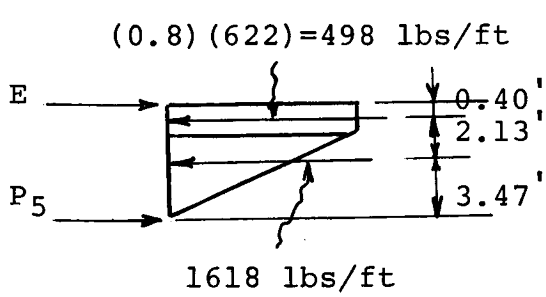
$P_1(6)=1618(4.53)+(1741)(1.40)$
$=7320+2440=9760$ lbs.

P_1 = 1628 lbs/ft

B = 1741+1618 -1628=1731 lbs/ft



C=D =1865 lbs/ft



$P_5(6)=498(0.4) + (1618)(3.53)$
$=200 + 4090 = 4290$ lbs

P_5 = 715 lbs/ft

E = 1618 +498 - 715= 1401 lbs/ft

EXAMPLE 3 (cont.)

P_1 = 1628 lbs/ft.

P_2 = 1731 + 1865 = 3596 lbs/ft.

P_3 = 2 (1865) = 3730 lbs/ft.

P_4 = 1865 + 1401 = 3266 lbs/ft.

P_5 = 715 lbs/ft.

If struts are located at 6 foot intervals along wall, then design strut loads are:

P_1 = 9800 lbs

P_2 = 21600 lbs

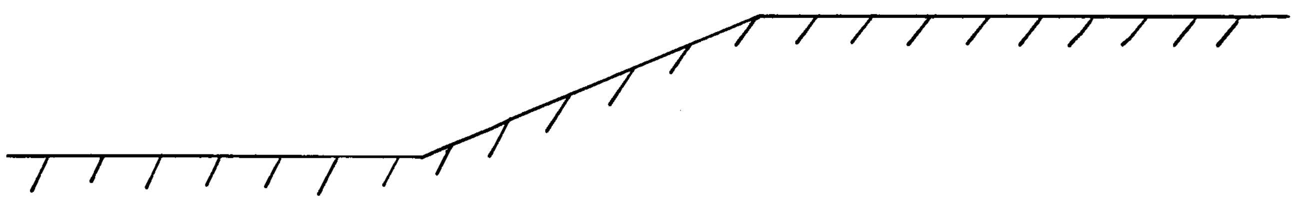
P_3 = 22400 lbs

P_4 = 19600 lbs

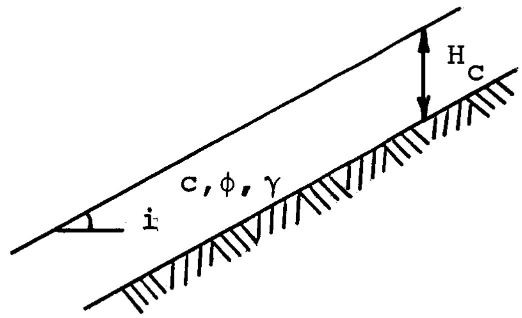
P_5 = 4300 lbs

Struts should be designed for a safety factor appropriate for the material used for the strut.

SLOPE STABILITY



EXAMPLE 1 - Infinite Slope

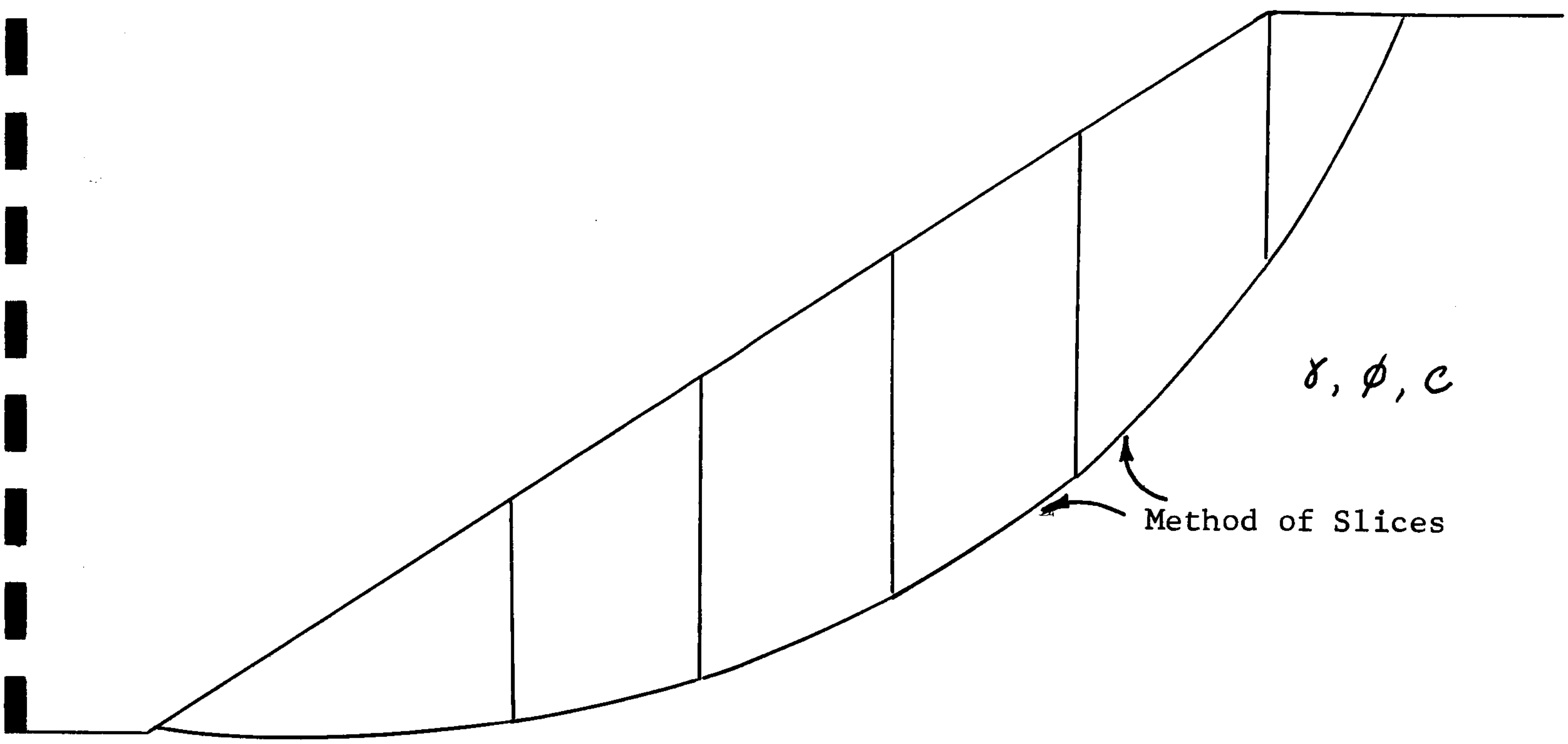


$$H_c^{max} = \frac{c}{\gamma} \frac{1}{\cos^2 i\,(\mathrm{TAN}_i - \mathrm{TAN}\phi)}$$

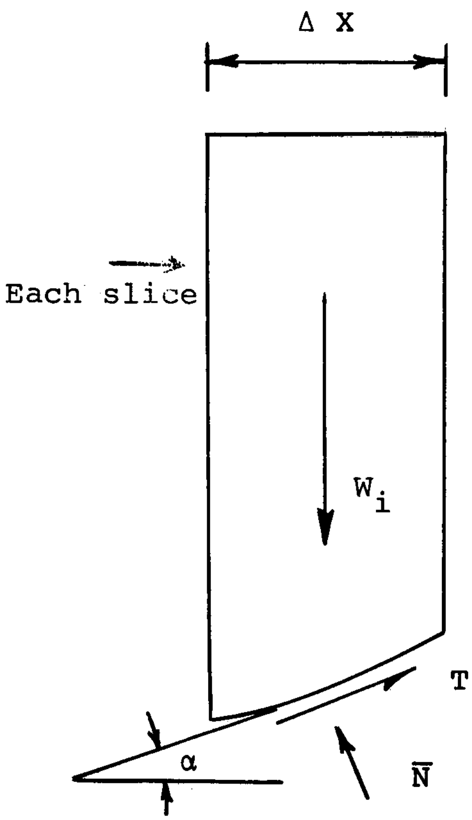
FOR C=0,

$$H_c^{max} \to \infty \quad \text{for } i \leq \phi$$

EXAMPLE 2 - Slope Analysis: Simplified Bishop Method



1. Assume trial failure surface
2. Divide failure mass into slices
3. Analyze stresses on each slice
4. Determine F for given surface
5. Repeat until minimum F is found



$$T = \tau \, \Delta X \sec \alpha \qquad \overline{N} = \overline{\sigma} \, \Delta X \sec \alpha$$

$$\tau = \frac{1}{F} (\overline{c} + \overline{\sigma} \tan \overline{\phi})$$

To find $\overline{\sigma}$, $\Sigma V = 0$

$$W_i - \frac{1}{F} (\overline{c} + \overline{\sigma} \tan \overline{\phi}) \, \Delta X \tan \alpha - (\overline{\sigma}) \, \Delta X = 0$$

$$\therefore \overline{\sigma} = \frac{W_i - \frac{1}{F} \overline{c} \, \Delta X \tan \alpha}{\Delta X \left(1 + \frac{\tan \overline{\phi} \tan \alpha}{F}\right)}$$

$$F = \frac{\Sigma \left[\overline{c} \, \Delta X + (W_i) \tan \overline{\phi}\right] \frac{1}{M_\alpha}}{\Sigma W_i \sin \alpha}$$

where $M_\alpha = \left(1 + \frac{\tan \alpha \tan \overline{\phi}}{F}\right) \cos \alpha$

Iterate to find F, safety factor.

EXAMPLE 2 (cont) Equation for safety factor according to simplified Bishop Method